A
STUDY
OF
THE
POTENTIAL
OF
REMOTE
SENSORS
IN
URBAN
TRANSPORTATION
PLANNING

"FEASIBILITY STUDY OF THE

APPLICATION OF SATURN/

APOLLO AUTOMATED DATA

CAPABILITIES TO PROBLEMS

OF THE ENVIRONMENTAL IMPACTS

OF URBAN TRANSPORTATION"

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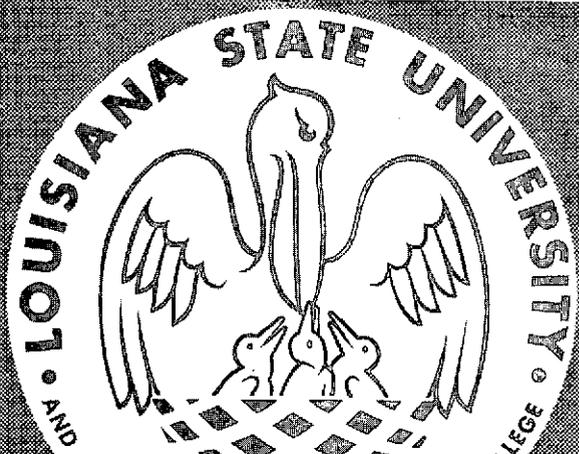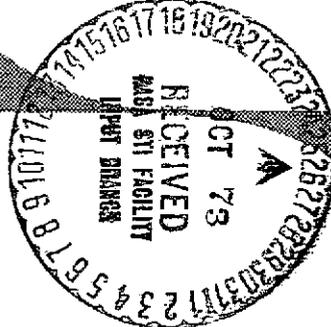
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DEPARTMENT OF CIVIL ENGINEERING

A STUDY OF THE POTENTIAL OF REMOTE SENSORS IN

URBAN TRANSPORTATION PLANNING

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ACKNOWLEDGEMENTS

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ABSTRACT

During the past decade great advances in both the art and science of the methods used in the transportation planning process have taken place. Today, now that this process is generally understood and documented, time can be devoted to researching new methods of obtaining the information necessary to implement the process. To this end this report discusses the potential uses of remotely sensed data as applied to the transportation planning process.

The transportation planning process can be divided into three general phases: (1) data gathering; (2) analysis; and (3) decision-making. The data gathering phase is typically the most expensive and most error-prone portion of the process. By utilizing the remote sensing technology developed by the National Aeronautics and Space Administration in the various space programs, it is hoped that both the expense and errors inherent in the conventional data collection techniques can be avoided. Additional bonuses derived from the use of remotely sensed data are those of the "permanent record" nature of the data and the traffic engineering data simultaneously made available.

This report discusses concisely the major mathematical modeling phases and the role remotely sensed data might play in replacing conventionally collected data. Typical surveys undertaken in the overall planning process determine the nature and extent of travel desires, land uses, transportation facilities and socio-economic characteristics. Except for the socio-economic data, data collected in the other surveys mentioned can be taken from photographs in sufficient detail to be useful in the modeling procedures.

It is hoped that NASA will pursue this subject in a pilot project where remotely sensed data is collected simultaneously with ground control data. Only in a planned coordinated project will the validity of this procedure in the large scale planning process be proved.

CHAPTER I

INTRODUCTION

The demand for and allocation of natural resources at present is reaching a record high, whether on a local, regional or global level, at the same time that supplies are dwindling or quality is deteriorating. If the per capita resource demand of the whole world were the same as that in the United States, the maximum sustainable world population would be limited to 600 million. The impending shortage of certain important resources makes necessary their wisest possible management and our adopting of the most recent technological developments that would facilitate the work of urban planners, foresters, agriculturists, hydrologists, and other resource managers (Figure 1).

In the fast-growing field of remote sensing--the acquiring of information through the use of cameras and related devices such as radar and thermal infrared sensors, all operated from aircraft and spacecraft--several useful developments have taken place. Most are designed to aid in the acquisition of better and more timely resource information and, hence, lead to better resource management.

1.1 Remote Sensing

In the broadest sense "remote sensing" means reconnaissance at a distance. In our work, we are interested in acquiring data needed to facilitate transportation planning studies with the use of man-made remote sensors.

The most-used remote sensing device, the photographic camera, was invented over one hundred thirty years ago. It allowed man for the first time to obtain a permanent and unbiased record of the man-made and natural features of the observed terrain. Along with

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FIGURE 1. SOURCES AND USES OF REMOTELY
SENSED DATA (from Branch, 1971, p. 82)

the improvements in photography and surveying came the science of

terrestial photogrammetry.[*] Although aerial photography from kites

and balloons was done before the turn of the century, the invention

of the airship and the airplane were responsible for the development

of two new sciences:

- Photogrammetry—measurement of objects from their photographic image, and

- Photo interpretation—identification of these objects

Although the science of aerial photography as a means of obtaining

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[*] Photogrammetry is the science or art of obtaining reliable measurements from photographic images.

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data has been developed to a high degree of reliability, it has a great disadvantage because it registers only the visible wavelengths of the electromagnetic spectrum (Figure 2) which makes it subject to the unpredictability of atmospheric conditions. This has motivated man to search for new types of sensors sensitive to other wavelengths in the spectrum that are not affected by atmospheric conditions. Today we have airborne sensors developed to function in the ultraviolet, visible, infrared, and microwave regions of the electromagnetic spectrum. Two major developments have caused this remarkable growth:

- The ability to place sensing instruments into orbit around the earth

- The developments that came about as a consequence of cold and hot war reconnaissance.

Regardless how advance remote sensors might be today, in order to utilize the information they gather requires the joint effort of employing modern sensors, data processing equipment, information theory and processing methology, communication theory and devices, space and airborne vehicles, and large systems theory and practice for the purpose of carrying out aerial or space surveys of the earth's surface and its dynamic behavior.

1.2 Remote Sensing in Engineering Applications

The available techniques of aerial sensing being used by engineers may be classed into three groups:[*]

1. Air reconnaissance--direct visual examination of the site from the aircraft.

2. Air photo interpretation--study of visual light as recorded on aerial photographs.

3. Aerial electromagnetic sensors--detection of radiation by aircraft mounted devices which convert energy to an electrical signal which can be quantitatively measured and displayed in forms such as a TV-like image or a profile.

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[*] G. F. Sowers, "Remote Sensing for Water Resources. Civil Engineering. Feb. 1973, pp. 35.

WAVELENGTH

.03Å	.3Å	3Å	30Å	300Å	.3μ	3μ	30μ	300μ	.3cm	3cm	30cm	3m	30m	300m	3km	30km	300km

| Gamma Rays | X rays | Ultra-violet. | V I S I B L E | Infrared | radar (microwave) | Ultra high radio Frequency | Low audio Frequency | A.C. |

ATMOSPHERIC TRANSM.

Magnetometers — Black & White Color photo — Thermal Sensor Scanner Spectrometer — K-band radar — X-band radar — Long wave Lenght Synthetic aperture radar — REMOTE SENSORS

Radioactivity — Cathode discharge — Gas tubes — Masers — SUN — Flash — Heat lamps — Cavity resonators — Electronic circuits — SOURCES

Ionization detectors — Phosphors — Photographic — Thermal — Visual — Quatum detectors — Antennae and circuits. — DETECTORS

10^{20}	10^{18}	10^{16}	10^{14}	10^{12}	10^{10}	10^8	10^6	10^4	10^2	1

FREQUENCY (cycles/sec.)

THE ELECTROMAGNETIC SPECTRUM

1.3 Electromagnetic Spectrum

Every object in the universe is constantly generating radiation caused by matter's atomic and molecular activity. Most of this radiant energy travels in wavelengths ranging from 10^{-14} meters to 10^{14} meters, and frequencies ranging from 10^{23} cycles/sec. to 10^4 cycles/sec.

The electromagnetic spectrum classifies, according to wavelength and frequency, all energy that moves with the constant velocity of light in a harmonic wave pattern. Therefore it is the electromagnetic spectrum which is of primary concern in considering the uses and limitations of remote sensing. The visible-light portion of the electromagnetic spectrum is just a narrow slit of the overall electromagnetic spectrum.

Remote sensing hardware, however, is not limited to operate in the visible-light portion of the electromagnetic spectrum only. Some systems of remote sensing are designed to use sonic and mechanical vibrations in a medium through which the energy waves can propagate from source to sensor. An example of this latter type of sensing system is the sonar used for underwater detection.

Despite the existence of other types of energy which can be utilized, the amount of information that can be obtained from remote sensing through electromagnetic energy is so great that it reduces almost to insignificance that obtainable from any other energy spectrum.

The minimum energy unit in electromagnetic radiation is the photon. Energy changes occur in photons as a consequence of energy-matter interaction, although electromagnetic waves do not interact between themselves. In empty space electromagnetic radiation may propagate without limit. Nevertheless, in most real applications propagation occurs through a media, in general, the atmosphere, and reflects or dissipates in matter such as objects on the earth's surface.

As mentioned before, all electromagnetic radiation travels

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at the same velocity, i.e., the velocity of light. The electro-
magnetic waves differ from each other in wavelengths, frequency
and energy. The basic relationship between frequency and wave-
length is given by the following relationship

$$F = \frac{v}{\lambda} \; a \qquad \text{where}$$

F = frequency

λ = wavelength

a = proportionality constant (depends on unit used)

And since in the electromagnetic spectrum v is constant
and equal to the velocity of light e where $e = 3 \times 10^8$ meters/sec.

$$F = \frac{e}{\lambda} \; a$$

so if F is expressed in cycles/second

λ is expressed in meters

e is expressed meters/second

then $\qquad a = \dfrac{(\text{cycles/sec.}) \; (\text{meters})}{(\text{meters/sec.})}$

a = cycles

and $\qquad F = \dfrac{3 \times 10^8}{\lambda}$ (cycles/sec.)

$$\lambda = \frac{3 \times 10^8}{F} \quad \text{(meters)}$$

(Recently the term "hertz" has become widely accepted as a substi-
tute for cycles/second.)

From the above relationships it can be deducted that the
difference between visible light, infrared radiation, and X-rays,

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for example, would be their interaction with matter. The intensity
of radiation is simply the number of photons per unit time and area.

When a photon of any specific energy strikes the boundary
of a solid object, many interactions are possible. Energy can be
either[*]

1. Transmitted, i.e., propagated through solid water

2. Reflected, i.e., returned unchanged to the medium

3. Absorbed, giving up its energy in the form of heat
   or matter

4. Emitted or remitted by the matter (a function of
   temperature and structure) at the same or different
   wavelength

5. Scattered, i.e., deflected to one side and lost, ulti-
   mately to be absorbed or further scattered.

These different interactions give origin to transmission,
reflection, absorption, emission and scattering of electromagnetic
energy. Figure 3 shows some important characteristics of the
electromagnetic spectrum in the operational range of remote sensing.

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[*] L. W. Hom, Remote Sensing of Water Pollution, Journal of
Water Pollution Control Federation. Oct. 1968. pp 1730
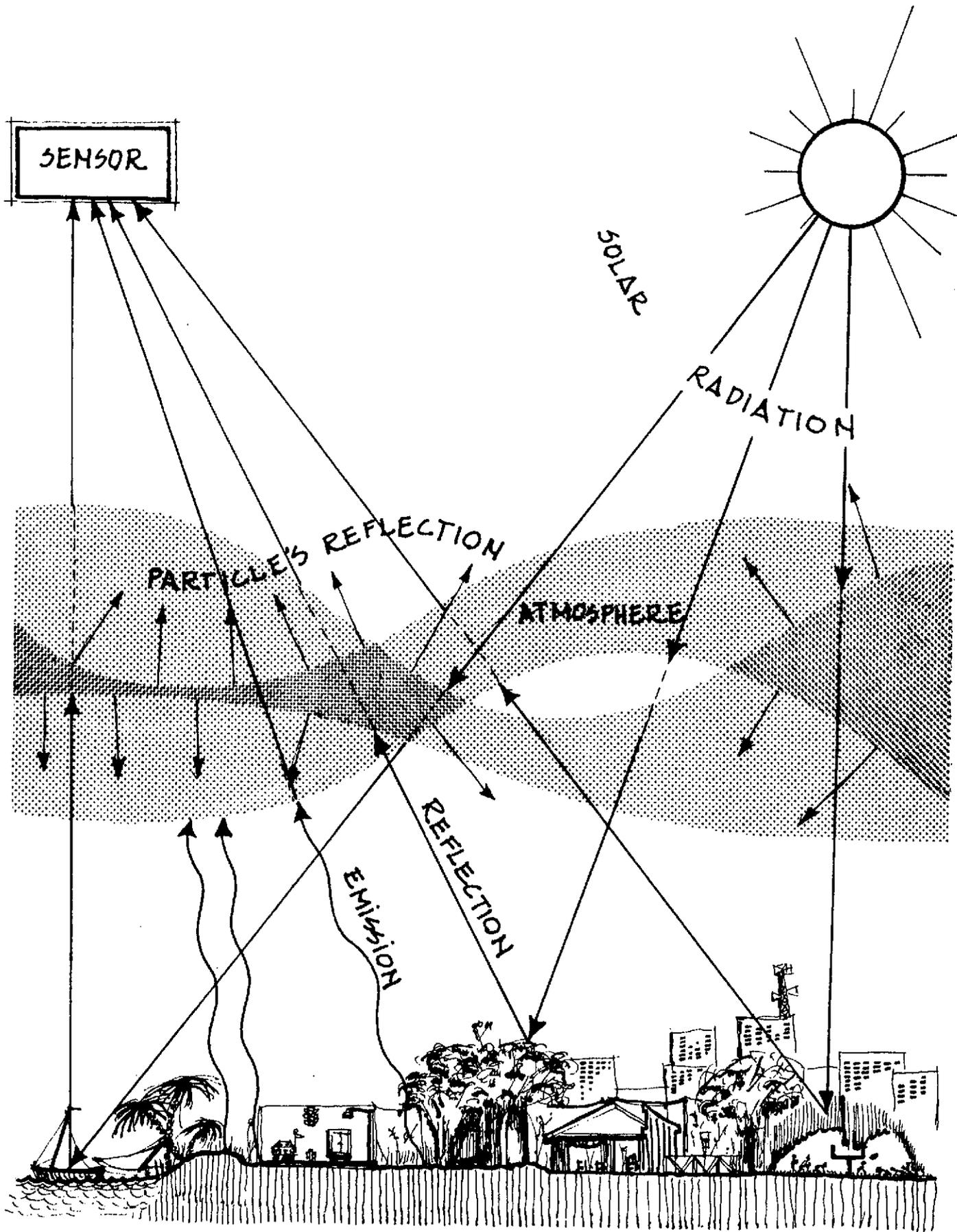
FIGURE 3.   NATURAL ELECTROMAGNETIC ENERGY SOURCES
USED FOR REMOTE SENSING

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CHAPTER II

REMOTE SENSORS

Remote sensors can be defined as optical, mechanical, or electrical devices which record data relating to a phenomena separated by some intervening distance from the recording instrument.

In order for remote sensing systems to operate, several conditions are necessary:

1. An energy source to radiate electromagnetic energy

2. A target, or material, which will interact with the electromagnetic waves of the energy source and consequently radiate further electro-magnetic waves

3. A propagating medium to transmit the waves

4. A detector to sense the desirable electromagnetic waves

Aerial sensors are classified in different ways depending on the characteristic being considered. According to the data output generated, they can be:

1. Imaging sensors that produce a photo-like image as output (Examples: black and white camera, infrared, and radar)

2. Non-imaging sensors that produce a meter reading or a chart track output (Examples: geiger counters, magnetometers, and radiometers)

Further, according to the electromagnetic energy source, sensors can be classified as passive or active.

2.1 Passive Sensors:

Passive sensors are designed to collect emitted and reflected radiation from surfaces with the energy source independent of the recording instrument. The radiation recorded by these sensors

includes reflected solar electromagnetic energy. (Figure 4)

Types of sensors included in this category are photo-
graphic cameras, thermal infrared sensors, microwave scanners,
and spectrometers. Each type is designed to operate in a speci-
fied portion of the electromagnetic spectrum. Thus each registers
different types of data and consequently is subject to different
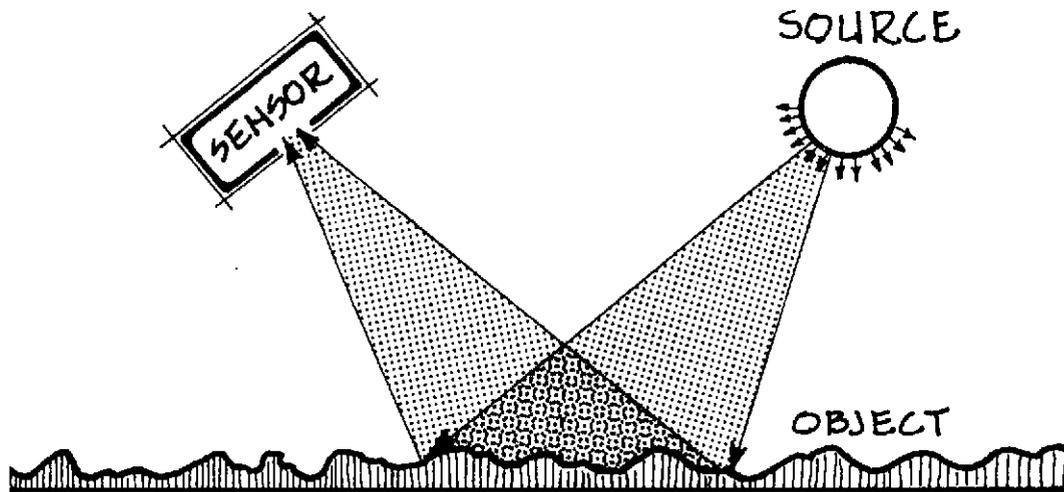
FIGURE 4.   THE PASSIVE SENSOR

constraints. According to the operational wavelengths, they can
be grouped into four categories:

     1.   Visible-light sensors

     2.   Infrared sensors

     3.   Microwave and radar sensors

     4.   Spectrometer interferometers

2.1.1   Visible-Light Sensors

These sensors, recording tonal and textural variations
visible to the eye, produce an optical image or photograph. The
photographic camera is the best known example. Although sensors
using visible light possess higher resolution than other sensory
systems, they are operational only under adequate light and minimum

cloud conditions. Cameras in this category include:

1. Conventional
2. Trimetrogon
3. Panoramic
4. Stereostrip
5. Multiband or multispectral

2.1.1.1 Conventional Aerial Camera--the most common remote sensing instrument (Figure 5):

Basically this camera is the same as a conventional camera with some special features added to it. Photographic film can be sensitized to wavelengths from about 0.3μ to 1.2μ, a spectral band about three times as broad as the human eye. Figure 6a shows the distribution of radiant energy from the sun in range from .3μ to .8μ. Figures 6b and 6c show the reflected energy of a blue object when struck by the sun's energy. Some typical film sensitivities are given in Figure 7.

Normal printing paper is sensitive only to ultraviolet and blue energy and insensitive to green, red or infrared energy. Pan-chromatic film is sensitive to ultraviolet, blue, green and red energy, but not to infrared energy. Infrared film is sensitive to ultraviolet, visible, and infrared energy.

2.1.1.2 Trimetrogon Camera:

This consists of three lenses and film magazines on a mount taking vertical and oblique photographs simultaneously (Figure 8).

2.1.1.3 Panoramic Camera:

This type of camera (Figure 9) makes possible the coverage of a large area in a single exposure with very high resolution. Basically, the panoramic camera consists of a movable scanning arm which rotates the lens from side to side, with the film held against a semicircular plate.

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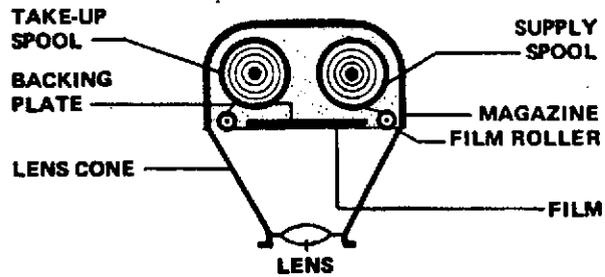
FIGURE 5. CONVENTIONAL AERIAL CAMERA
(from Branch, 1971)
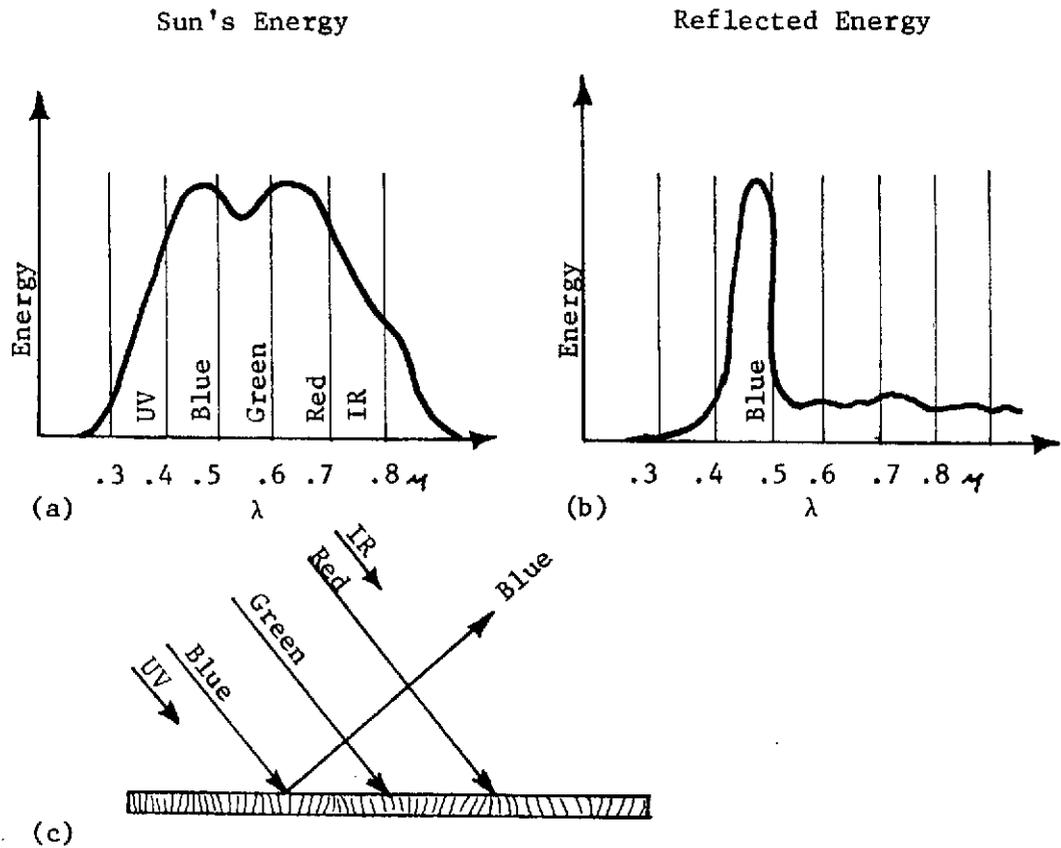
FIGURE 6.   ENERGY REFLECTED FROM A BLUE OBJECT
(from Kiefer and Scherz, 1970)

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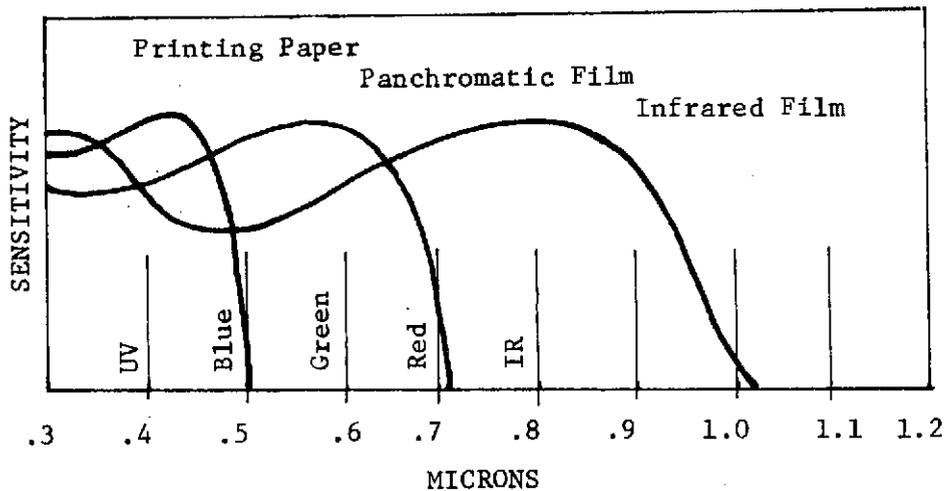
FIGURE 7. SENSITIVITIES OF VARIOUS BLACK AND WHITE EMULSIONS

(from Branch, 1971, p. 204)
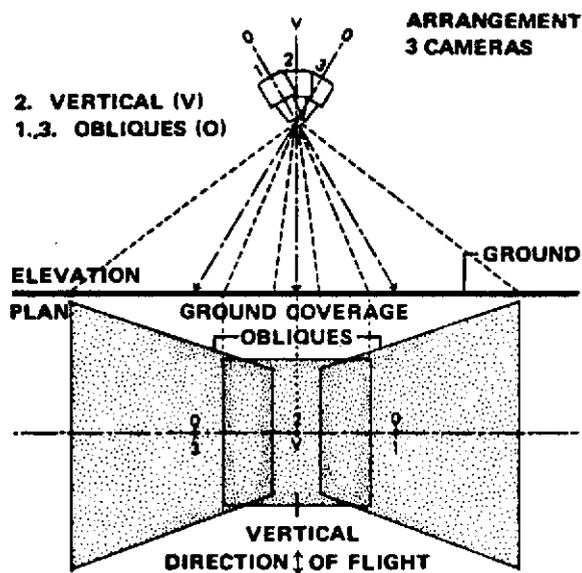
FIGURE 8. TRIMETROGON CAMERA

(from Branch, 1971)

13
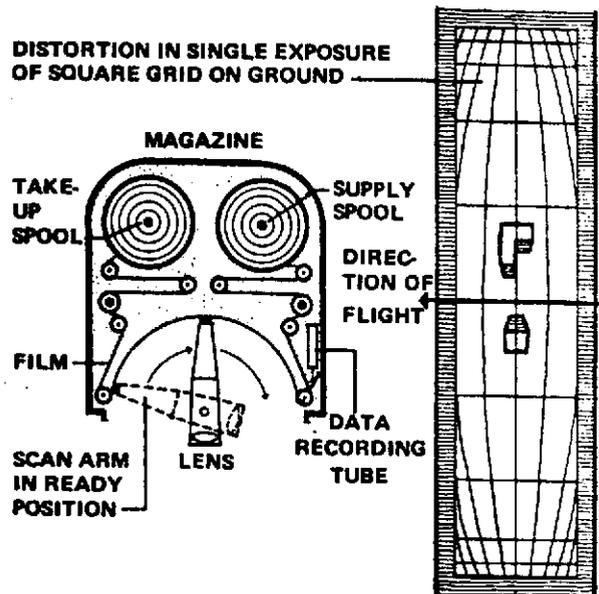
FIGURE 9. PANORAMIC CAMERA

(from Branch, 1971)

2.1.1.4 <u>Stereostrip Camera</u>:

This camera has a continuously advancing film which is syn-
chronized with the ground speed of the airplane (Figure 10). The
camera needs no shutter.

2.1.1.5 <u>Multiband Cameras</u>:

These cameras take simultaneous photographs of the same sur-
face area in several bands of the spectrum. The film most commonly
used is sensitive to wavelengths throughout the visible spectrum
and into the near and far infrared. Figure 11 shows a 9-lens model.
Cameras with 4 lenses are also available

2.1.2 <u>Infrared Sensors</u>

These sensors register electromagnetic impulses of longer
wavelengths than those of visible light. The thermal infrared

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FILM MAGAZINE

OFFSET
IMAGES
ON FILM

FILM ROLL

FILM SPEED
RELATED TO
GROUND SPEED

SLIT

STEREO LENSES
NO SHUTTER

LENS CONE

FLIGHT
DIRECTION

THIN OFFSET STRIPS
ON GROUND AS
RECORDED AS
FILM MOVES

IMAGES
DISPLACED
OUTWARD
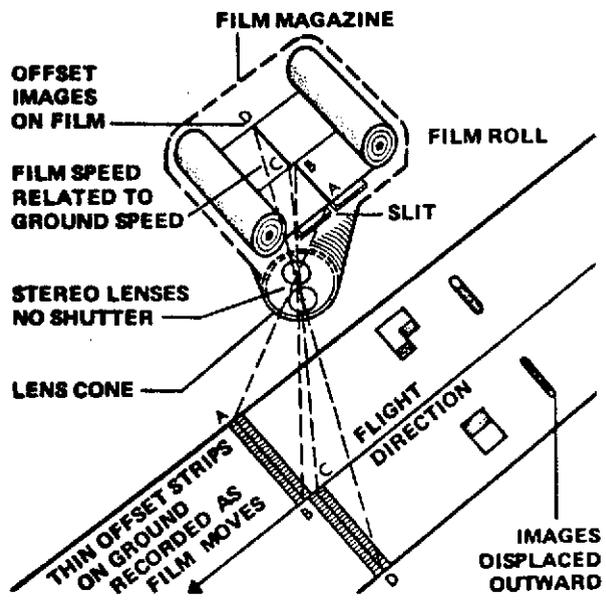
FIGURE 10. CONTINUOUS STEREOSTRIP

(from Branch, 1971)
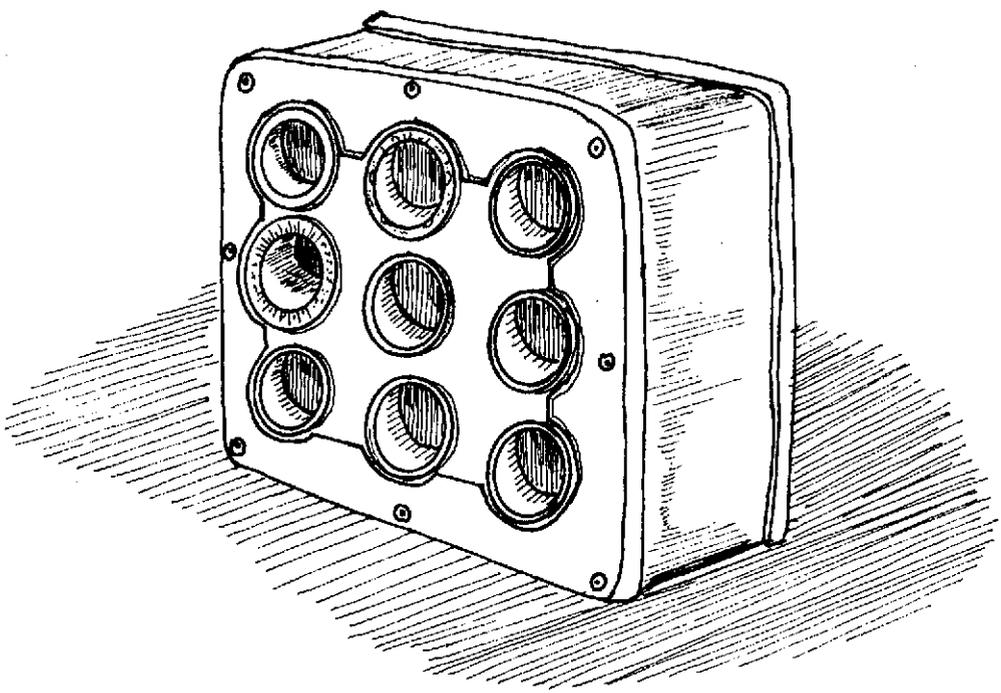
FIGURE 11. MULTIBAND CAMERA

sensor electronically records heat radiated from objects (Figure 12).
Resolution of detail is not as good as that by visible light sensors;
however, thermal infrared sensors are not restricted to daylight
operation, and additionally, they possess some ability to penetrate
clouds.

Infrared energy can also be detected with the use of special
films in conventional cameras. At present, the most-used example
is Kodak Aerochrome Infrared color film, which records certain colors

AIRCRAFT

INSTANTANEOUS FIELD OF VIEW

DISTORTION OUTWARD

GROUND COVERAGE OF EACH SCAN

SUCCESSIVE FILM SCANS

STRAIGHT RAILROAD

FLIGHT DIRECTION

1. FACES OF ROTATING MIRROR 2. PARABOLIC
MIRROR 3. COOLING JACKET 4. DETECTOR 5. AMPLI-
FIER-MODULATOR 6. ROTATION AXIS 7. CATHODE-
RAY TUBE 8. FILM SPOOL 9. RECORDING OF OPTICAL
SCAN ON PHOTO FILM
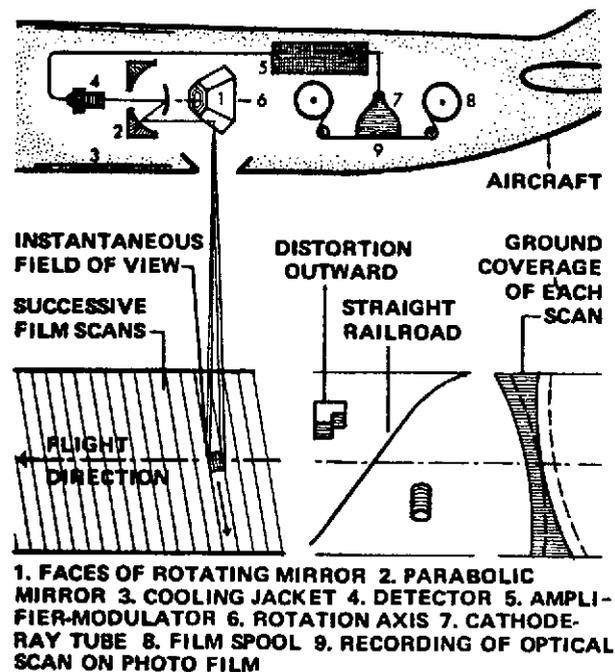
FIGURE 12. OPTICAL-MECHANICAL THERMAL
SCANNER (infrared)
(from Branch, 1971)

falsely (Figure 13). (The World War II forerunner of this film was
called Camouflage Detection Film.) The cyon-forming layer is sensi-
tive to infrared energy; the yellow-forming layer, to green light;
and the magenta-forming layer to red light. A yellow filter is

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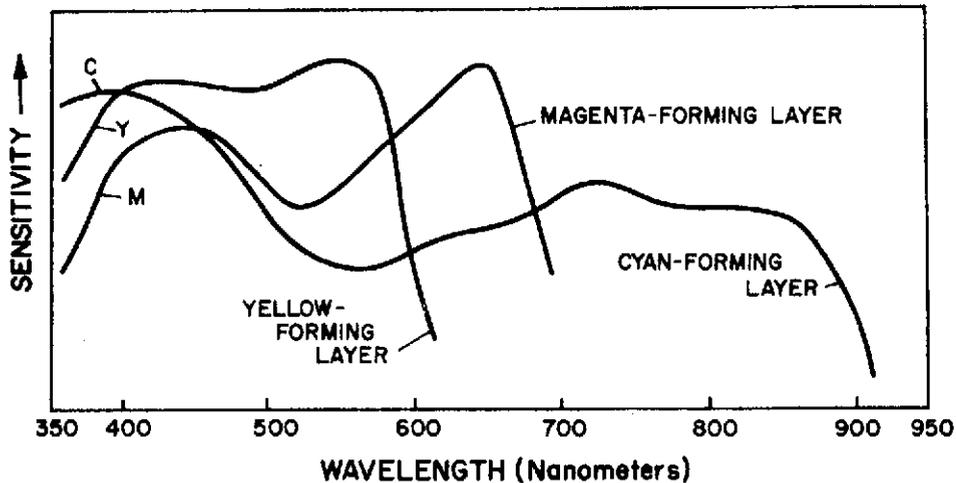
FIGURE 13. SPECTRAL SENSITIVITY OF KODAK AEROCHROME INFRARED

FILM, TYPES 2443 AND 3443

(Eastman Kodak Company, 1972)

used over the camera lens to cut out blue and UV light, which af-
fects all three layers.

2.1.3 Microwave and Radar Sensors

These sensors utilize still longer electromagnetic wave
lengths than the infrared sensors. They can detect the roughness
of the object's surface, but produce an image electronically. At
present, imaging radars possess the poorest resolution capabilities
among the four sensor types, but they have the greater advantages
of covering a much larger area from the same altitude and the ability
to operate effectively both day and night under virtually all weather
conditions.

2.1.4 Spectrometer Interferometer

Spectrometers, which detect very short wavelengths (a micron
or less) are excellent for locating radiactive substances, even
when used several thousand feet from the ground. Designed to operate

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at the nuclear and electron levels of atomic structure, they are especially sensitive to infrared radiation. The readings can be digitized and transformed into spectrographic images. There is one disadvantage. They cannot penetrate clouds without interference.

2.2 Active Sensors

These sensors are more elaborate than the passive sensors because, along with a receiver, they must also have an emitter to broadcast a specific electromagnetic energy. Active sensors irradiate the surface under investigation with an electromagnetic beam of a particular wavelength and then sample a portion of the beams reflected back to the receiver. Examples of active sensors include imaging radar and scatterometers (Figure 14).
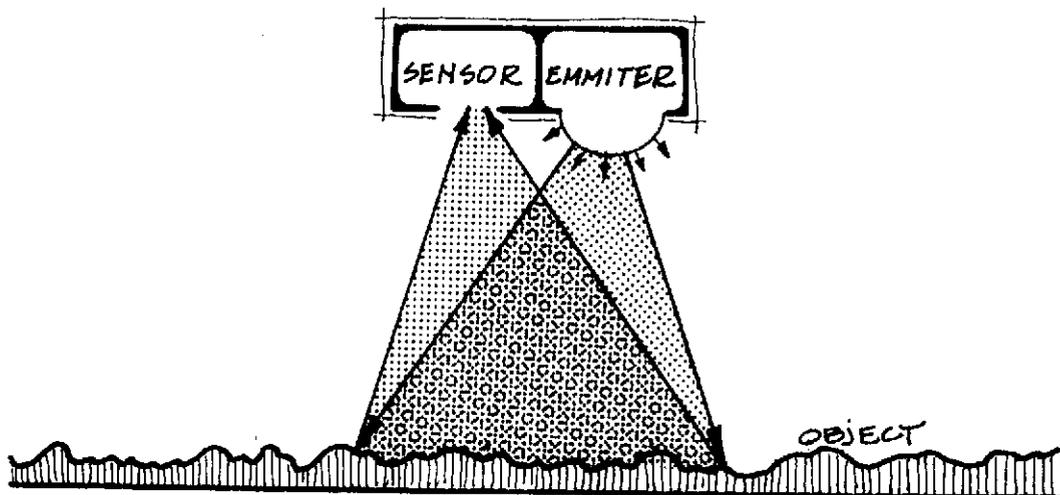
FIGURE 14. THE ACTIVE SENSOR

2.2.1 Side-Looking Airborne Radar

Commonly referred to as SLAR (Figure 15), this sensor has all-weather and 24-hour usefulness and the ability to penetrate vegetation. A transmitting antenna sends microwave energy out one side of the airplane. This energy strikes a thin lobe-shaped area

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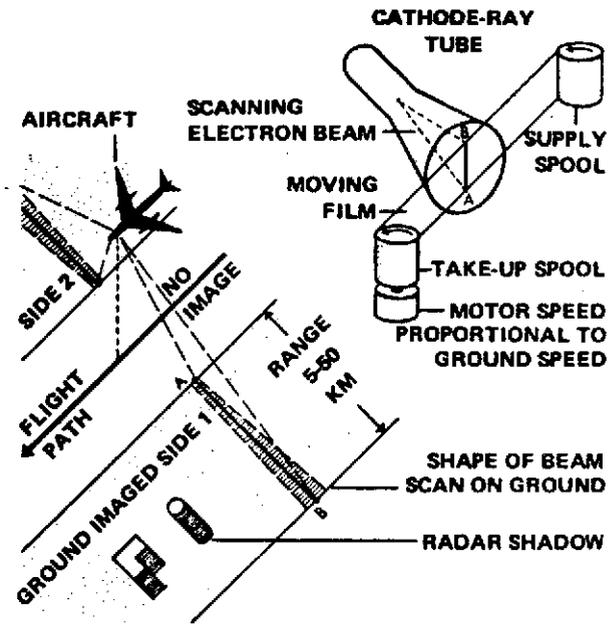
FIGURE 15. SIDE-LOOKING AIRBORNE RADAR

(from Branch, 1971)

on the ground; a receiving antenna collects the reflected energy. The strength of the reflected signals determines the brightness of the points on a cathode ray tube, which are photographed on film.

Because radar operates at much longer wavelengths than spectrometers and infrared sensors, it has poorer resolution of detail.

2.2.2 Magnetometers

There are also sensors that utilize wavelengths shorter than those in the visible spectrum, the best known being the magnetometer. Its principal commercial and research application has been to detect magnetic anomalies in the crust of the earth. Flight altitudes for these sensors have to be low (200 feet for mineral detection, 2000 feet for oil exploration) because higher altitudes result in a rapid decrease in the strength of the readings. At present, use of magnetometers in aerial sensoring is very limited.

CHAPTER III

AERIAL PHOTOGRAPHY VERSUS OTHER AERIAL SENSORS

The selection of a remote sensing system will depend ulti-
mately on the characteristics of the entity or phenomena to be stud-
ied. For example, although Side-Looking Airborne Radar (SLAR) has
the advantage of all-weather operation, it is not suited for trans-
portation study due to poor resolution. It is conclusive that, at
this point in the state-of-the-art, aerial photography seems to be
the most appropriate method. Nevertheless, for the future it seems
that infrared and multispectral aerial photography have the greatest
potentials, but research and experimentation will decide this question.

Aerial photography has both advantages and disadvantages for
transportation studies:[*]

3.1 <u>Advantages</u>:

  1. Photographic lenses and films have superior resolution
      in comparison to television or optical-mechanical
      scanners.

  2. Aerial photography and film processing are simpler than
      the electronic circuitry used to make useful the data
      obtained with other sensors.

  3. Photographs offer better spatial orientation and re-
      quire little rectification.

  4. Human interpreters can identify features from normal-
      size negatives or prints.

  5. The equipment is simpler, smaller, and lower in cost.

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[*]National Academy of Sciences. Remote Sensing with Special
Reference to Agriculture and Forestry. 1970. pp. 69-70.

3.2 Disadvantages:

1. Ordinary photographic films require clear weather and sunlight.

2. Film processing imparts a delay that is not true for real-time systems in which data is transmitted through telemetering and television.

3. Photographic systems used in space vehicles must be shielded from radiation to prevent fogging of film.

4. Procedures are lacking for human and automatic interpretation as well as for the storing and computing of data.

5. Photographic sensors use only a very small portion of the electro-magnetic spectrum.

3.3 From Imagery to Data

Remote sensing has the potential for revolutionizing all data collection systems. The expected increase in data extraction from satellite- and aircraft-generated imagery provides the impetus and a greater concern for gathering information from maps or imagery automatically in terms of patterns--described as points, lines, or areas--and interpreting or counting the phenomena to be associated with them. At present, data extraction is done through human interpretation and automated spectral analysis.

Human interpretation of aerial imagery is the oldest and most reliable method at the present time. There has been no substitute because of the capacity to recognize patterns and to tolerate moderate geometric distortions as well as user-optimum exposure and processing conditions. The major setback is the slowness of both interpretation and extraction of data from the image.

Automated spectral analysis, as a means to obtain data from imagery, is at the present time still in the experimental stage. Automated interpretation to digital form, automated pattern recognition, and automated report generation are possible, but not fully operational. The great asset is the speed by which data could be obtained from the imagery; therefore, it is not surprising that much research is now being directed toward the

development of techniques for both automatic pattern recognition and spectral signature analysis.

The most prospective system for data acquisition from imagery would be a real-time system that would interface the human operator with a computer.

As far as transportation planning is concerned, vehicle identification apparently lends itself better to an automatic data collection system rather than any geographic, geologic, or other urban phenomena.

CHAPTER IV

INITIAL DECISIONS TO BE MADE IN THE

TRANSPORTATION PLANNING PROCESS

4.1 Vehicle Trip or Person Trip

Once a decision has been made about the basic type of distribution model to be used, choices remain as to the manner in which the model can be used to estimate travel patterns. In this particular study, we will describe the Gravity Model (Chapter X).

One of the first decisions, whether to use vehicle trips or total person trips, of course will depend on the objectives and needs of the study as well as the size of the area involved. The prime determinant in the decision is whether or not a modal split analysis will be considered. Modal split analysis is the technique by which auto driver and transit passenger trips are distributed separately via each mode. Where modal split analysis is being made, total person trip distributions are necessary. In some studies where transit trips are relatively unimportant (generally in smaller urban areas), modal splits are not used whatsoever and a vehicle trip model is utilized.

4.2 Trip Purpose Classification

Another necessary decision is the number and types of trip purposes to be used in the model. There may be as few as one or as many as nine different categories of trip purposes. As a general rule, it is desirable to take into consideration the number of trips in each category and their particular trip length characteristics which will be used in later stages of trip distribution calibration.

The amount of data, preparation time, computer time and analysis time must also be considered. Several large urban areas have used the following trip purpose categories:[*]

    a.   <u>Home based work</u> -- These trips between a person's place of residence and a commercial establishment for the purpose of work.

    b.   <u>Home based shop</u> -- Those trips between a person's place of residence and a commercial establishment for the purpose of shopping.

    c.   <u>Home based social-recreation</u> -- Those trips between a person's place of residence and places of cultural, social and recreational activities.

    d.   <u>Home based school</u> -- Those trips by students between the place of residence and school for the purpose of attending classes.

    e.   <u>Home based miscellaneous</u> -- All other trips between a person's place of residence and some form of land use for any other trip purpose.

    f.   <u>Non-home based</u> -- Any trip which has neither origin nor destination at home regardless of its purpose.

    g.   <u>Truck trips</u> -- All trips by truck.

    h.   <u>Taxi trips</u> -- All trips by taxi.

Most small urban area transportation studies have been using three trip-purpose categories, home-based work, home-based non-work and non-home based. Home-based work trips are those defined previously in category (a). Other home-based trips are those defined in categories (b) through (e) above, and categories (f) through (h) are classified as non-home-based trip group.

4.3 Treatment of External Trips

A decision has to be made as to the treatment of external trips, i.e., those trips which have one or both ends outside the study area. In some studies, the external cordon stations have been considered as fictitious zones and have been assumed to produce and

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[*]Bureau of Public Roads. <u>Calibrating and Testing a Gravity Model for Any Size Urban Area</u>, Nov. 1968. p. III-9.

attract trips in a manner similar to the internal zones. This procedure nevertheless is undesirable because of the following reasons:[*]

1. Trips made by those persons living inside the cordon area may exhibit different trip length characteristics than those made by persons who live outside the area.

2. External-to-External trips are associated with the study area for only a small portion of their total journey and therefore, exhibit distribution characteristics which have nothing at all to do with the study area.

However, if the number of external trips is small compared to the overall number of trips, cordon stations can be assumed to produce and attract trips as the internal zones.

It is desirable to treat the total universe of trips as three distince types (Figure 16):

1. Internal trips -- Those trips with both ends of the trip within the cordon area

2. External trips -- Those trips with one end inside the cordon and one end outside the cordon

3. Through trips -- Those trips with both ends outside the cordon.

[*]_Ibid._, p. III-10
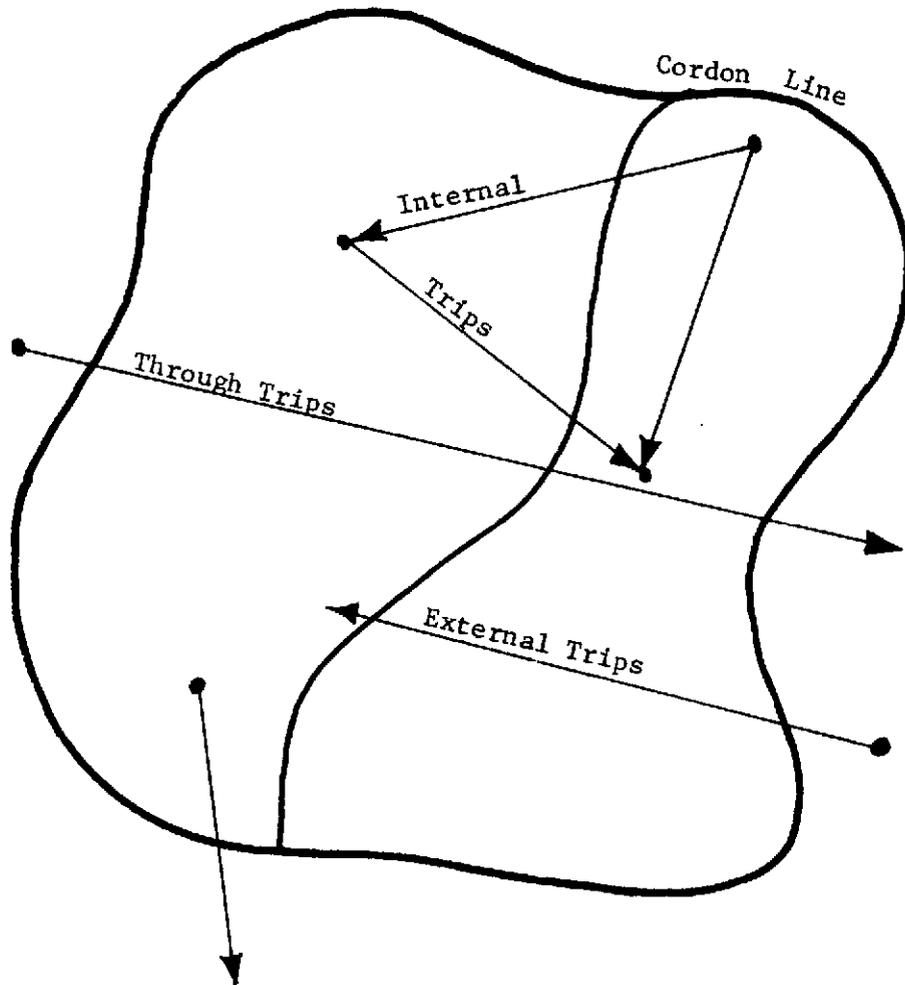
FIGURE 16.   TRIP CLASSIFICATION

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CHAPTER V

DATA REQUIREMENTS FOR A COMPREHENSIVE

TRANSPORTATION PLANNING STUDY

The first stage of any transportation study is the collec-
tion of data. Data is collected through surveys especially designed
to be part of the transportation study or through previous studies
and miscellaneous publications that might be available. Generally
this is the most costly and time demanding phase of the transportation
planning process. Not only must data be collected concerning the ex-
isting physical facilities, but also detailed information must be ob-
tained about socio-economic conditions, land uses, travel character-
istics and other pertinent information.

In the opinion of many transportation planners, the existing
methods of obtaining basic data are too expensive and time consuming.
Therefore a more comprehensive data bank or information system should
be developed. During the data collection phase of previous transpor-
tation studies, the overlapping efforts of various planning agencies
has been apparent. Remote sensing has the potential to reduce such
wasted effort by providing a common data base to the individual
agencies. With such a broad data base available, attention could
then be turned to the optimizing of data available from other sources:
for example, census data. Annual field updating of data could also
be more easily accomplished.

Basically the data requirements for comprehensive transpor-
tation studies according to the United States Department of Trans-
portation (Policy and Procedure Memorandum 50-9, Nov. 1969) are:

1. Economic factors

2. Population

3. Land use

4. Transportation facilities (including mass transportation)

5. Travel patterns

6. Terminal and transfer facilities

7. Traffic control features

8. Zoning ordinances, subdivision regulations, building codes, etc.

9. Financial resources

10. Social and community value factors

This is a general guideline followed by all transportation studies, but very seldom will different transportation studies give the same weight to each of the above categories which is a reflection of the particular conditions of each study area. Nevertheless, some basic data surveys and inventories are common to all transportation studies:

1. Travel data

2. Land use

3. Transportation facilities

4. Socio-Economic characteristics

Data for transportation planning studies can be categorized as:[*]

1. Primary or essential data: Data that has to be gathered directly from its source. This category includes data from land use surveys, home interviews, and roadside interviews.

2. Supplemental or secondary data: Data that does not have to be gathered directly from its source, and can generally be found in public records. Data from the Bureau of the Census, Sanborn Insurance maps, industrial directories, etc., are included in this category.

A similar breakdown of data was done for a comparative study of five major transportation planning studies done by Creighton,

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[*] F. E. Horton and R. Wittick. p. 5-4.

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Hamburg Planning Consultants. The data requirements and the utility
of each data category were examined for the following urban areas:*

1. The Chicago Area Transportation Study (CATS)

2. The Niagara-Frontier Transportation Study (Buffalo
    and Niagara Falls, N.Y.)

3. The Southeastern Wisconsin Regional Land Use Transportation
    Study

4. The New Castle County Program (Wilmington, Del.)

5. The Tucson Area Transportation Study

Table 1 shows a comparative analysis of primary data surveys
done in five studies; Table 2 shows secondary data with typical
sources.

Time and cost constraints make it impossible to interview the
entire population so samples must necessarily be taken, the sizes
of the samples depending on the size of the urban area. Table 3
shows the recommended sample size according to population.

5.1 Travel Pattern Survey

For urban areas of over 50,000 population, it is considered
essential that travel for all types of trips, i.e., zone-to-zone,
zone-to-external station and external station-to-external station,
by automobile, transit, truck and taxi be established by purpose and
time. This is usually done by conducting a comprehensive origin-
destination (O-D) study. Before any survey, i.e., origin-destination
survey, can be done the following parameters have to be established:

- Determination of limits of study area

- Cordon line around study area

- Division of study area into appropriate small aerial
  units or zones. (Appropriate implies compatibility with
  the network to be analyzed, uniformity of land usage,
  recognizable boundaries consistent with other data such
  as census data.)

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*Creighton, Hamburg Planning Consultants. Data Require-
ments for Metropolitan Transportation Planning. National Cooperative
Highway Research Board Report 120.

TABLE 1

MAJOR PRIMARY DATA SURVEYS

Major Survey	Chicago	Buffalo	Milwaukee	Wilmington	Tucson
TRAVEL					
Home Interview	●	●	●	●	●
Truck-taxi Interviews	●	●	●	●	●
Roadside Interview	●	●	●	●	●
Railroad passenger ques.	o			o	
TRANSPORTATION FACILITIES					
Arterial Link inventory	●	●	●	●	●
Transit Link inventory	●	●	●	●	
Intersection Capacity Studies					o
Speed runs	●	●	●	●	●
Traffic Count Program	●	●	●	●	●
Parking Studies					o
Air-bus-rail terminal Studies		o			
Goods movement Studies		o			
Person-miles travel		●			
LAND USE					
Land area measurement	●	●	●	●	●
Floor space measurements	o	o			
Public Utilities			●		
Soil & Surface Water			●		
Parks & Open Space studies			●		
SOCIO-ECONOMIC					
Personal Opinion Questionnaire			o	o	
Household History Questionnaire			o		
Industrial Management Survey			o		

● - Essential
o - Marginal Utility Only

(from Creighton, Hamburg, 1971)

TABLE 2

SECONDARY DATA WITH TYPICAL SOURCES
OF SUCH DATA

Data	Typical Sources
Population	U.S. Bureau of the Census
Birth & death rates	City or County/Parish Clerk
Number of dwellings & other structures	Census, Sanborn, Special surveys
Employment data	State Department of Labor
Plans for land uses, by type	City/County/Parish planning bds.
Zoning maps & regulations	City/County/Parish planning bds.
Topographic flood plain data	U.S. Geological Survey
Historical Buildings	Special Survey (generally)
Barriers map	Local planning agencies
Automobile registration data	State Dept. of Motor Vehicle reg.
Transit fares	Local transit company
Parking costs	Special survey may be required
Travel cost data for road types	Published sources
Transit travel cost	Local transit company
Accident cost data by road type	Miscel. published sources
Accident cost data-transit type	Local transit company
Road construction cost	State Highway Department
Transit construction costs	Miscel. published sources
Arterial widths & pavement cond.	City/Parish/County Engineering Dept.
Truck registration data	State Dept. of Motor Vehicle Reg.
Transportation plans	Highway Engineering Department
Transit revenue passengers	Local transit company
Detailed maps, air photos	Highway Engineering Department
Other social value data	Special survey might be required

(from Creighton, Hamburg, 1971)

TABLE 3

RECOMMENDED SAMPLE SIZE

Population		Sample	
50,000 - 150,000	12-1/2%	(1 out of 8 D.U.)
150,000 - 300,000	10 %	(1 out of 10 D.U.)
300,000 - 500,000	8-2/3%	(1 out of 15 D.U.)
500,000 - 1,000,000	5 %	(1 out of 20 D.U.)
Over 1,000,000	4 %	(1 out of 25 D.U.)

(from Horton and Wittick, p. 5-13)

• Screen line to check travel data

Of all the primary data, the O-D data are usually the most expensive and most detailed and is the basic data source of the travel patterns of the population. An O-D survey will include the following:

• Home interview -- household record
              -- person trip record
• Truck and Taxi interview
• Roadside interview -- external survey

The general information to be collected from an O-D survey is:

• Geographic location of each end of the trip
• Purpose of the trip
• The mode of travel
• Land use at each end of the trip
• Socio-Economic characteristics of the trip maker

5.1.1 Home Interview

In the home interview, the sampled households are asked to give the previous day's travel schedule and some household attributes such as sample address by dwelling unit types, location of

the sample, number of persons residing in the unit, number of passenger cars owned, with or without garages, etc. The personal attributes include certain information about each occupant such as sex, race, age, occupation, etc. Comparative home interview data asked in the five transportation studies mentioned previously are given in Tables 4 and 5.

Persons and household attributes have two principal applications in the planning process:

1. As a reference point in the projection of population, employment and auto ownership

2. As prime determinants of present and future trip generation and modal choice.

5.1.2 Roadside Interview

Roadside interviews are conducted at cordon crossings (stations) leading into the study area. Vehicles are stopped and information is asked about the trip in progress. By asking where the automobile is garaged, duplication of trips by study area residents is eliminated and a check on the accuracy of external trips by vehicles garaged inside the study area is established. Stations are normally set up on all but minor roads which cross the cordon, so that about 95% of the traffic crossing the cordon passes through the interview stations. About 50% of all traffic passing through a station is interviewed. Traffic checks and sometimes interviews are made inside the study area and these are generally referred to as internal checks or interviews as opposed to external interviews which are done along the cordon line. Internal checks are done along imaginary lines referred to as internal cordons or screen lines which follow natural or man-made barriers (canals, railroad tracks, etc.) and divide the study area into two parts (Figure 16). These counts and/or interviews are compared to those made in the home interviews for accuracy checks. The type of survey to be implemented in any study area would depend upon its particular characteristics. For instance the Federal Highway Administration (FHA)

TABLE 4

HOME INTERVIEW--HOUSEHOLD RECORD

Data	Data Collection and Use				
	Chicago	Buffalo	Milwaukee	Wilmington	Tucson
Structure type	o	o	●	●	●
Type of living quarters	o	●	o	●	
Interview address	●	●	●	●	●
Number of passengers	●	●	●	●	●
Number of persons	●	●	●	●	●
Persons age 5 and up	o	o	o	o	●
Overnight visitors	o	o	o	●	
Time at present address	o			●	●
Previous address	o			o	
Time at previous address	o				
Sex	o	o	o		
Race	o	o	o	●	o
Age 5 & up making trips	o	o	o	o	o
Age 5 & up not making trips	o	o	o	o	o
Total trips made	o	o	●	o	●
Persons age 16 & up	o		o	o	
Driver status–age 16 & up	o	o	o	o	
Number of walking trips	o				
Income		●	●	o	
Occupation		o	o		
Industry		o	o		
Age		o	o		
Worked on travel day		o			
Year-around resident					●
Part-time resident; months lived at address					●
Persons employed					●
Auto driver trips					●

● – Data collected and used
o – Data collected

(from Creighton, Hamburg, 1971)

TABLE 5

HOME INTERVIEW--PERSON TRIP RECORD

·Data	Data Collection and Use				
	Chicago	Buffalo	Milwaukee	Wilmington	Tucson
Sex	●	○	●	○	○
Race	●		●		○
Age	○	○	●	○	
Occupation	○	○	○	●	○
Industry	○	○	●	○	○
Origin location	●	●	●	○	○
Destination location	●	●	●	●	●
Purpose "from"	●	○	●	●	○
Purpose "to"	●	●	●	●	●
Land use at origin	●	○	○	●	○
Land use at destination	●	●	●	●	●
Starting time of trip	○	●	●	●	●
Arrival time of trip	●	●	●	●	●
Mode of travel	●	●	●	●	●
Blocks walked at origin	○	○	●	○	●
Blocks walked at destination	○	○	●	○	●
Number of persons in car	○	○	●	○	○
Kind of parking	○	○	○	○	○
Screenline control points	●				●
Expressway used	○	○			
Principal route of travel	○				○
First work trip	○				●
Expressway entrance		○			
Expressway exit		○			
Automobile available			●	○	
Income		○	●	○	
Structure			○		
Density			○		
Car Pool					○
Park & Shop					○

● - Data collected and used
o - Data collected

(from Creighton, Hamburg, 1971)

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recommends that for cities with a population under 5,000, only an external cordon survey should be conducted. There are proven techniques available to synthesize internal trips where no home interviews are conducted. For cities with populations between 50,000 and 75,000 a variety of survey techniques are suggested by the FHA depending upon the particular traffic patterns of the city. For areas where predominant flow is on through routes, only an external cordon is recommended. If most traffic is oriented toward the central business district (CBD), then an internal-external cordon survey is recommended (internal cordon line surrounding CBD). If CBD is congested and has associated parking problems, but few problems exist outside this area, then an external cordon parking survey is recommended. For cities with major problems throughout the city, an external cordon and home interview survey is recommended. Table 6 shows a comparative analysis of roadside interviews done by the five major studies mentioned previously.

5.1.3 Truck and Taxi

Again, the purpose of the truck and taxi survey is to obtain data describing the origin, destination, purpose and time for each trip. Table 7 shows a comparative analysis of truck and taxi surveys done in the five major studies previously mentioned. These surveys are the least consistent of the three basic travel surveys. This might be attributed to the varying importance of truck-taxi travel in particular urban areas.

5.2 Land Use

Very seldom does a land use inventory require a complete field inventory. This method of data collection generally is too expensive and time consuming to be implemented. Most transportation studies use more economical methods, for example in the Chicago (CATS) land use study was obtained through transcription of utility meter cards, fire insurance records and telephone subscriptions supplemented by field checks. Land use is used as input to models

TABLE 6

ROADSIDE INTERVIEW

Data	Data Collection and Use				
	Chicago	Buffalo	Milwaukee	Wilmington	Tucson
Sample location (station)	o	o	●	●	●
Hour period beginning	o	o	●	●	●
Direction (in/out)	●	●	●	●	●
Vehicle type	●	o	●	●	●
Number of passengers in vehicle	o	●	●	●	●
Trip origin location	●	●	o	o	●
Trip destination location	●	●	●	●	●
Trip purpose	●	o	●	●	●
Land use at destination	●	●	●	●	●
Where is vehicle garaged	o	●		●	●
Route of exit and/or entrance, through trips	o	o	o	●	o
Screen line crossed	●				●
Canadian registration		o			
Truck load		o		o	
Entrance or exit points to thruway		o			
Land use at origin			o	o	o
Number of stops			o		
Commodity			●		
CBD origin			●		
CBD destination			●		
Through trip					
New Jersey route used for station 01				o	
Trip purpose, through trips					o

● - Data collected and used
o - Data collected
    (from Creighton, Hamburg, 1971)

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TABLE 7

TRUCK-TAXI TRIP RECORD

Data	Data Collection and Use				
	Chicago	Buffalo	Milwaukee	Wilmington	Tucson
Sample location	●	o	o	o	
Vehicle type	●	o	●	●	●
Garage address	o	o	o		
Business-industry	o	o	●		●
Number of trucks owned or rented	o	o			
Total trips reported	o	o	●		●
Trip origin location	●	●	●	o	●
Trip destination location	●	●	●	●	●
Trip purpose & origin	o	o	●	o	o
Trip purpose destination	o	o	●	●	o
Land use at origin	●	o	o	o	o
Land use at destination	●	●	●	●	●
Starting time of trip	o	o	●	●	●
Arrival time of trip	o	o	●	●	●
Principal route of travel	o				o
Truck or taxi loading		o		o	
Expressway used		o			
Expressway entrance		o			
Expressway exit		o			
Number of stops reported	o			o	
Commodity carried			o		o
CBD origin			o		
CBD destination			o		
Year of manufacture					o
Unladen weight					o
Use of pick up					o
Control points					●

● - Data collected and used
o - Data collected

(from Creighton, Hamburg, 1971)

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of urban growth and development which will forecast changes in
the economic activity of the study area. Also land use data is
used in trip generation analysis where trip generations become a
weighted dependent variable of land use. Table 8 shows different
sources used in land use inventory in seven individual transpor-
tation studies. In urban areas that would require a complete in-
ventory, the acquisition of four basic sets of data are recommended:

1. Location and identification of every residential and
   non-residential area within the study area

2. A complete listing of all houses within the cordon
   line (to be used for selecting a sample for the
   hone-interview travel inventory)

3. An inventory of streets and street intersection.

4. A listing of address numbers by block and by zone

Table 9 illustrates a comparative analysis of land use data col-
lected by the five major transportation studies previously men-
tioned. It can be noticed that there is a considerable variation
in the type of data collected by the different studies. Through
this comparative analysis it was not possible to measure the effect
of the degree of aggregation of land uses by category or the accuracy
of the resulting data. In the Chicago and Buffalo studies, floor
space data were collected. This was expected to yield more accurate
trip generation in the CBD and other high activity centers. Although
the floor area data provided useful insights into the structure of
the city and the CBD, they were only marginally useful from a trans-
portation planning aspect.

5.3 Transportation Facilities

The third major inventory necessary for a comprehensive
urban transportation study is a survey of the existing physical
transportation system. The first task to be conducted is to in-
ventory the existing street system according to use and function.
The highest type of facilities serve predominantly long trips,
carries relatively high traffic volumes, and generally serves the
most dense land uses. As the facilities proceed to a lower quality

TABLE 8

LAND USE DATA SOURCES

	Chicago	Denver	Buffalo	Penn. Jersey	Pittsburg	Puget Sound	St. Paul-Minneapolis
Sanborn Insurance map	•	•	•		•		
Land use plan from planning agency	•	•				•	•
Aerial Photographs	•	•	•	•	•	•	•
City directories, telephone directories, etc.	•	•				•	•
U.S.G.S. Survey maps (1:24,000)	•		•	•	•	•	•
Utilities meter records	•						
Building information from owners and managers association		•				•	
Complete field inventory			•	•	•		

(from Horton and Wittick, p. 3-8)

TABLE 9

LAND USE INVENTORY

Data	Data Collection and Use				
	Chicago	Buffalo	Milwaukee	Wilmington	Tucson
Address-location	●	●	●	●	●
Type of land use	●	●	●	●	●
Vacant un-usable	●				
Vacant zoned by type	●	●			●
Secondary land use code				●	
Secondary land use of parcels in 100's acres				●	
Number owner-occupied dwelling units				●	
Number renter-occupied dwelling units				o	
Number non-white occupied dwelling units				●	
Non-conforming land use code				●	
Number persons dwelling on parcel				●	
Number of uses				●	
Number of secondary uses				●	
Watersheds			●		
Dwellings		●			

● - Data collected and used

o - Data collected

(from Creighton, Hamburg, 1971)

TABLE 10

DATA FOR EXISTING
TRAFFIC SERVICE

1	Volume
2	Travel Time
3	Street capacity
4	Accidents
5	Parking
6	Control Devides

(from Horton and Wittick,
p. 5-19)

TABLE 11

DATA FOR PHYSICAL
STREET SYSTEM

1	Widths
2	Pavement types
3	Age and condition
4	Riding quality
5	Sidewalk condition
6	Curb condition
7	Gutter condition
8	Stormdrain conditions

(from Horton and Wittick,
p. 5-20)

service they will carry lower traffic volumes, at low speeds, and generally shorter trips. A standard classification of traffic facilities (Figure 17) is:

- Expressways
- Major arterials
- Collectors
- Local streets

Other additional data necessary in the inventory of major streets is right-of-way, roadway length, type and condition or surface, capacity, size and type of parking locations.

The operational characteristics of the existing system must also be inventoried. The capacities of the major streets and intersections, the traffic volume for each segment of the major streets, the speed of traffic movement on various parts of the system during peak and off-peak flow conditions, and traffic accident data all should be included in the transportation facilities inventory.

Data about the transit system are also included in this phase, such as transit routes, passenger fare distribution, revenue vehicle miles, average seating, route miles, terminal-to-terminal running times and regularity of service. Tables 10, 11, and 12 show typical types of variables included in these studies.

A parking facilities inventory is generally included in the

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FIGURE 17. TYPICAL PHYSICAL PARAMETERS IN THE
URBAN TRANSPORTATION STUDY
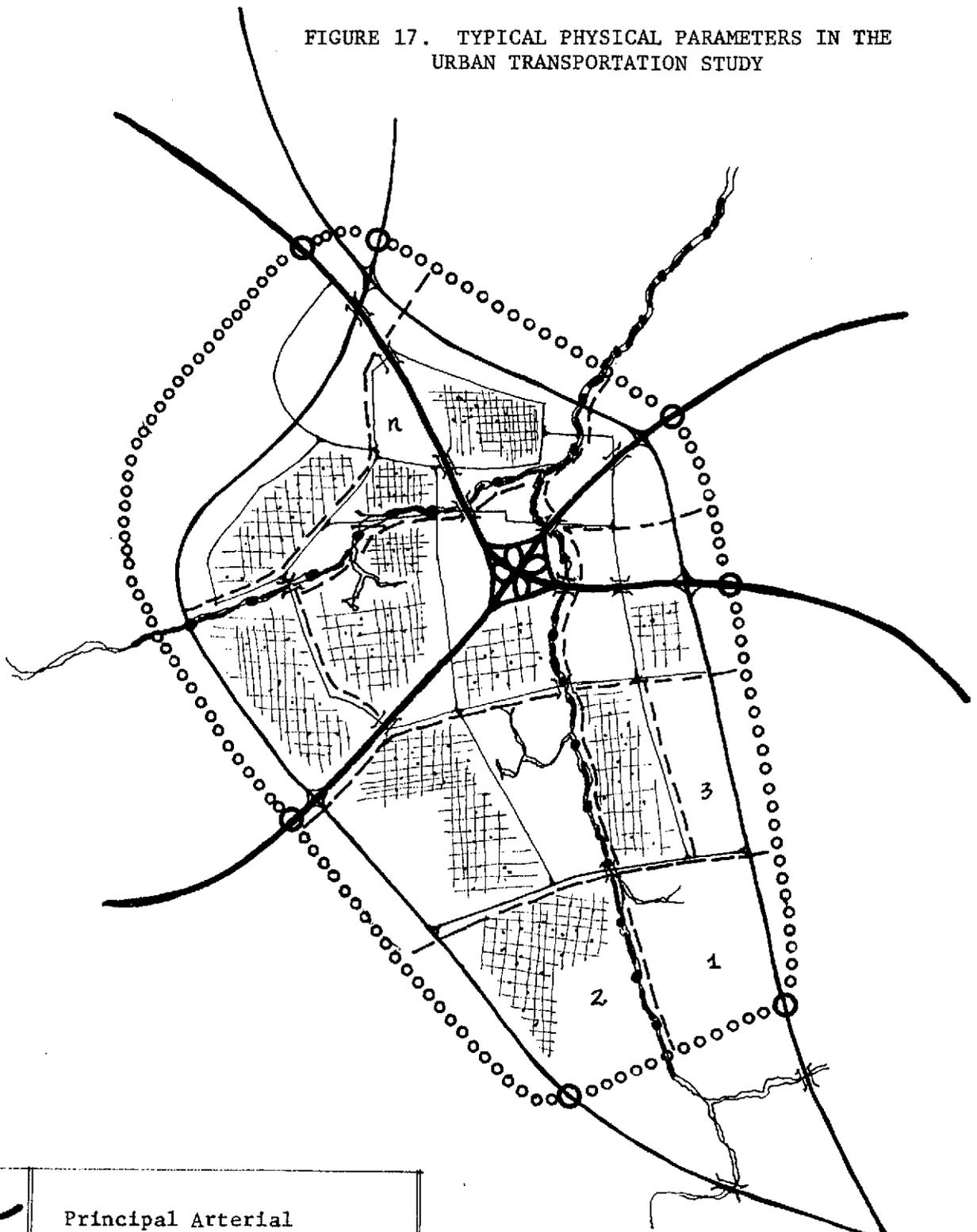
〰	Principal Arterial			
〰	Minor Arterial	ₒₒ°ᵒᵒᵒₒ	External Cordon	
⌢	Collector	•—•—	Screen Line	
▦	Local (Urban Development)	— — —	Traffic Zone	
⌇	Natural Barrier	O	External Interview Station	
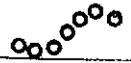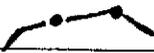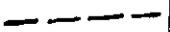
TABLE 12

DATA FOR EXISTING TRANSIT
SERVICE

1	Routes and Coverage
2	Transit route inventory
3	Passenger load data
4	Service frequency and regularity
5	Transit running time
6	Transit speeds and delays
7	General operating data
8	Passenger riding habits

(from Horton and Wittick,
p. 5-20)

TABLE 13

DATA FOR PARKING SURVEY

1	Block
2	Facility number
3	Description
4	Type of parking
5	Restrictions
6	Time limits
7	Average hourly fee
8	Number of spaces
9	Spaces in use

(from Horton and Wittick,
p. 5-21)

general inventory of physical facilities but on some occasions parking facilities are inventoried separately. Table 13 shows typical variables used in parking facilities inventory.

5.4 Socio-Economic Characteristics

Generally, socio-economic data is obtained through the household interview and other primary and secondary sources mentioned before.

Economic data includes employment, per capita income, income consumption patterns, vehicle ownership, labor force, etc. Population characteristics are readily available from the Bureau of the Census, planning agencies and other sources.

Socio-economic data is used as input to trip generation models. Once this model has been established, these socio-economic factors are forecast and future trip generation rate can be estimated (see Chapter IX, Section 9.2).

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CHAPTER VI

DATA ACQUISITION AND REMOTE SENSING IMAGERY

The previously-discussed surveys and data are the basic elements for starting a comprehensive transportation planning study. Once the data collection phase has been accomplished and a transportation plan has been developed, it becomes of primary importance that the paln be kept up-to-date with what the FHA defines as continuous comprehensive transportation planning which serves:

1. to keep data up-to-date

2. as a check on the original transportation plan forecasts.

Data requirements for continuing transportation planning are similar to, although not as extensive as, those in the initial investigation.

Seven data fields should be continually updated on an areal basis (Walton and Kurthy, 1958):

1. Land Use (traffic zone, census tract, or others)

2. Population

3. Employment

4. Total Housing Units

5. Labor Force

6. Automobile Registration

7. Retail Sales

Some of these needs could be fulfilled by the use of data from the Census Bureau, which is updated every ten years.

Data obtained from remote sensing imagery can be classified according to the level of correlation (utility between data and imagery):[*]

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[*]Horton & Wittick." p. 5-23

1. First degree of correlation

2. Second degree of correlation

3. Third degree of correlation

6.1 First Degree of Correlation

This data can be extracted from aerial imagery with the highest level of utility. In this case, the particular data item might be measured or derived directly from the imagery. Included are link width, link right-of-way, intersection characteristics, number of lanes, and geometrics.

6.2 Second Degree of Correlation

Second degree data is that which can be sensed by imagery, but not measured or quantified, such as gross land use patterns and approximate size of residential, commercial, industrial, etc., areas.

6.3 Third Degree of Correlation

This data focuses on the utilization of information taken from imagery as surrogate measures for the actual data item desired. One example is housing quality.

6.4 Data Categories

According to spatio-temporal conditions, the data items necessary for a continuous comprehensive transportation planning study can be classified into:

Type I: Data that can be collected from imagery derived during single time period with surrogate measures identifiable for acquiring information on specific items.

Type II: Data that requires some form of temporal monitoring over a period of time in the collection process due to the spatio-temporal components of the items themselves.

Table 14 lists data items that can be obtained through single aerial imagery. For further information about Type I data, see

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Horton and Wittick)

In transportation planning, however, we are basically interested in the acquisition and interpretation of time-series data, i.e., Type II data, which are related to traffic density, the capacities of traffic facilities, etc. This type of data requires time-monitoring imagery. Generally, before such a system is set up, certain considerations and parameters depending on the data or conditions being studied, whould be established:

1. The number of days that the monitoring system will be operational--monitoring on more than one operation day will show daily variations.

2. The beginning and ending monitoring times of each operational day.

3. The selection of an appropriate time interval between imaging--generally, the time intervals should not be constant over a whole daytime period; rather, they should be dependent on peak and off-peak traffic occurrences, i.e., longer intervals at off-peak hours and shorter intervals at peak hours.

6.5 Potential Use of Remote Sensing in Travel Surveys

By selecting a sample of trips, it would be possible to determine the origin and desitnation of trips and the land uses of both the origins and destinations. From this information, along with aggregate socio-economic data obtained for the same areas, certain trip maker characteristics could be determined.

Traffic patterns can be used to determine the direction and intensity of flows on each major link in the transportation network. With this information collected for all the time periods, the approximate intensities of trip generation and attractions could be found on a zonal basis. Trip purposes could then be estimated on the basis of land use at the origins and destinations. Specific information such as average flow, link capacities, speed of traffic movement, and traffic control effectiveness should also be measurable from a monitored remote sensor. (Note that these traffic engineering considerations can be derived from aerial photography.)

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TABLE 14

DATA COLLECTABLE BY AIRBORNE REMOTE SENSORS

Aggregate Measures

     Population . . . .   P

     Motor Vehicle Registration . . . .   P

     Personal Income . . . .   P

     Employment . . . .   P

Land Use Areas

     Class of Activity . . . .   D

     Intensity of Activity . . . .   P

     Physical Limitations . . . .   D

Transit Facilities Inventory

     Length.   D

     Mode . . . .   D

     Terminal Facilities . . . .   D

     Parking . . . .   P

D = data obtainable directly from imagery

P = data obtainable indirectly with probabilistic values
    from imagery

    (from Horton and Wittick. p. 5-29)

However, to develop and <u>validate</u> generation, distribution, and assignment models from romotely sensed data, ground control data must also be collected in the conventional manner. To date, such correlated data has not been available. Thus, the practical application of remotely-sensed data to the total transportation planning process is still an unanswered question.

CHAPTER VII

TRANSPORTATION DATA ACCURACY CHECKS

The data obtained from the five basic transportation surveys (D.U. survey, internal survey, external survey, truck survey and taxi survey) has to be checked for accuracy, as well as classified into a format that would allow further study. The accuracy checks are very important because the reliability of the model to be built depends on it. Accuracy checks can be classified into two categories:[*]

    1.   Socio-Economic data checks

    2.   Travel data checks

7.1 Socio-Economic Data Checks

There are several socio-economic data sets that must be checked for accuracy:

- Dwelling units
  -- Total
  -- Occupied

- Population

- Number of automobiles

- Occupation of residents

- Employment

- School enrollment

- Income

The simplest test for the expanded dwelling unit data is to make a comparison of similar data from other independent sources such as the Bureau of the Census, utility companies, motor registration

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department, school board records, etc. It is not unreasonable to expect overall accuracy checks equal to or greater than 95% with no single transportation zone with less than 85% accuracy.

Census data can also be used to check persons /D.U./ zone, automobiles /D.U./ zone, total population/zone (if coincidental with census tracts), and a 90% or more accuracy check should be expected.

Occupation and industries in which residents are employed can be checked against data obtained from state employment offices, Chamber of Commerce, planning agencies, and other miscellaneous agencies.

If the transportation planning survey is three or more years away from the decimal census year then it becomes more difficult to check the surveyed data. In such a situation other independent sources of data must be found and historical trends taken into consideration. For example building permit offices, state and local planning agencies, state employment agencies, automobile registration, etc., are sources of data from which trends may be developed.

It is very important, once a travel survey begins, that the independent data be collected as soon as possible so that once the survey data is collected, coded and expanded, the accuracy checks can be made immediately.

7.2 Travel Data Checks

The accuracy of socio-economic data does not preclude that travel is or will be accurate; it merely means that the socio-economic data has been collected and expanded correctly.

7.2.1 Screenline Comparison

The best known method for checking trip data is the screen-line comparison. A screenline, as has been shown previously, is an imaginary line dividing the study area into two parts. Its purpose is to check the completeness and accuracy of the reported trip data. This is done by making manual classification counts of all vehicles crossing the screenline and comparing these counts, by hour, to the

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number of vehicle trips having an origin on one side and a destination on the other side as determined from the expanded interview data.

As shown in Figure 16, there are some factors that must be taken into consideration when locating a screenline:

- It must be entirely inside the study area

- It should follow natural or man-made obstacles in order to minimize double crossings and maximize reliability of cross-traffic counting. It must also follow traffic zone boundaries

- It should intercept large volumes of internal travel and minimum number of external trips

In some study areas the above mentioned guidelines might be impossible to follow due to particular geographic and/or spatial distribution of the urban area. In this case screenlines are not so reliable and adjustments must be made for the multiple crossings along the screenline.

There are several methods to accomplish screenline traffic counts--screenline interviews, hand-out postcards and visual license plate survey. In these interviews as little data as possible should be asked to avoid unnecessary delays and redundancies. Basic information to obtain is trip origin, destination, purpose, residence location and occupancy rate of the sampled vehicles. If screenlines cannot be logically located, cutlines and extensive traffic assignment checks are recommended. Cutlines are used across high traffic volume corridors or arterials. Somewhat less accuracy can be expected due to the possibility that some traffic will circumvent the cutline count station. Nevertheless, at least 80% accuracy check is expected. In some cases where "special traffic generators" have to be considered, i.e., universities, shopping centers, hospitals, airports, etc., a cordon line (internal cordon line) around these facilities is recommended.

In conducting an accuracy test, one must take into consideration that some trips may have been counted more than one time, e.g.:

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- Trips made by residents of the study area that crossed the cordon line. Theoretically, these trips are obtained twice--once in the dwelling unit survey (internal survey) and once in the external survey

- Trips made by resident (taxi passengers) which have been counted in the D.U. survey and in the taxi survey

- Personal truck trips made by residents counted in the D.U. survey and in the truck survey

- Through trips made by non-residents. Through trips are those that have an origin and destination outside the study area. Theoretically they are counted twice--once at the entering station and once at the departure station.

There is a difference of opinion in applying expansion factors to the above mentioned trips, except for through trips which have an expansion factor of .5.

After analyzing the multiple crossings along the screenline and having made the appropriate adjustments for multiple crossing, actual screenline comparisons might proceed. Differences between screenline traffic counts and trips generated from the survey can generally be attributed to two items:

1. Under-reported trips

2. Non-reported trips

Under-reported trips are those trips that were not obtained in the travel survey due to poor interviewing techniques. Appropriate adjustment techniques can help overcome this difficulty.

Non-reported trips are those trips made inside the study area by non-residents. Depending upon the particular urban area these trips might or might not be a problem. The common name given this type of trip is secondary non-home based trip.

A general procedure for checking survey travel data and screenline counts is to compare the expanded internal and external trip data with ground counts made at different points along the screenline.

Four basic tables that must be prepared for a screenline check are commonly called Tables A-1, A-2, A-3 and A-4.

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Table A-1 is to summarize auto trips only. In some instances, taxi trips are included in this table. The general format for Table A-1 is shown in Figure 18. Tables A-2 and A-3 are for truck trips and taxi trips respectively, and their formats are similar to Table A-1. Table A-4 is a summary of Tables A-1, A-2 and A-3.

7.2.2 Cordon Line Comparison

There are three tables that should be prepared for the cordon line traffic check. They are commonly called Tables A-5, A-6 and A-7.

Table A-5 is for passenger car trips. This table is used for comparing trips made by residents that cross the external cordon that have been recorded previously in the external cordon survey and in the home interview survey. In this table the appropriate trips from all the external stations are added together. A typical format is shown in Figure 19. Table A-6 is similar in format to Table A-5 but is for trips made by trucks registered in the study area. Table A-7 is a summary of Tables A-5 and A-6.

7.2.3 Trip Data Assignment Comparison

Traffic assignment is another valuable tool that can be used in determining the accuracy of trip data. In order to be able to use this comparison technique it is necessary to have an accurate area wide ground count. By assigning unadjusted trips to the present network, it is possible to get an area-wide feel for the adequacy of the trip data. Such comparisons as total trips assigned vs. total counted volumes, corridor checks, vehicle miles of travel, etc., can be used to check the adequacy of the trip data.

It is important to emphasize that as part of the overall trip data accuracy check, the transportation network is also calibrated, i.e., by assigning trip tables developed from the O-D survey to the existing network, imbalances between individual links in the network can be corrected. More about this particular

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subject will be explained in the following sections about trip
tables and the assignment model.

Once trips have been assigned to the transportation net-
work and accurate traffic counts have been obtained, the following
comparisons can be made:

1. Screenline Analysis: This check can be done by simply
   summarizing the total trips counted on the screenline
   and the total trips assigned to the links crossing the
   screenline and the total trips.

2. Corridor Analysis: By strategically locating cutlines
   across major traffic corridors, the total trips in each
   corridor can be counted and compared to trips assigned
   on the network. Examining total trips at each cutline
   will help overcome some of the deficiencies in an un-
   calibrated network.

3. Vehicle Miles of Travel: One of the statistic obtained
   from an assignment model is vehicle miles of travel
   (VMT) by different link classifications. These can be
   compared to the actual VMT computed from ground counts.
   Actual VMT is computed by summarizing the product of
   counts and length of link on as many of the trans-
   portation links as possible.

4. Total Vehicles: Another output of the traffic assign-
   ment model is a summary of total assigned volumes on
   the different links of the network. These can be com-
   pared to ground counts made on some of these links.
   This check also provides an area-wide indication of
   the completeness of the O-D survey. Theoretically,
   if all trips have been accounted for in the O-D survey
   and if area wide ground counts are complete and accu-
   rate, these two numbers should be about equal.

7.2.4 First Work Trip Comparison

Accuracy checks on first work trip can be done by selecting
several zones containing large numbers of employees from which em-
ployment figures can be obtained. The number of persons employed
in each zone may then be compared to the number of first work trips
made to specific zones as determined from the expanded survey data.
Employment figures can also be obtained by making an industrial
survey.

TABLE A-1. Comparison of Passenger Car Trips at Screenline No. __. (by Trip Purpose)
Location _____.

Hour Period	Expanded Trip Data								Total Ground Count	Percent $\frac{\text{Total Exp}}{\text{Total G.C.}}$
	Internal trips						External Trips	Total Trips INT + EXT		
	H-B Work	H-B Shop	H-B S/R	H-B School	H-B Other	Non-Home-based				
Totals										

FIGURE 18. BASIC TABLE TO FACILITATE SCREENLINE TRAFFIC CHECK

TABLE A-5. Passenger Car Trips Crossing Cordon Line,
made by Residents of the Area

Hour Periods	Expanded Internal	Expanded External	Percent Internal/External
Totals			

FIGURE 19. BASIC TABLE TO FACILITATE CORDON
LINE TRAFFIC CHECK

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7.2.5 Duplicate Truck and Taxi Trips

This check is done only if the truck and taxi trips represent at least 10% of total travel. The comparisons to be made are as follows:

1. For truck trips: "Personal Affairs" trips from the truck survey compared to the "Personal Affairs" trips made by truck as obtained from the home interview survey.

2. For taxi trips: "Taxi Passenger" trips from the home interview survey compared to total taxi trips obtained in the taxi survey.

7.2.6 Special Traffic Generator Trip Comparison

Trip checks for special traffic generators such as shopping centers, universities, airports, business districts, etc., are accomplished by comparing traffic counts at cordons surrounding these special generation zones to trips assigned to those zones. Also this check can be accomplished by summarizing and tabulating only those survey trips between all analysis zones and the special generator zone and comparing them to appropriate ground counts.

7.2.7 Mass Transit Trip Comparison

When mass transit trips are of sufficient magnitude, their accuracy can be estimated by comparing the total number of trips obtained from the internal survey with the total number of passengers carried on an average day as reported by the transit company. In areas or zones with a high concentration of mass transit trips, it is recommended to make a cordon line survey.

7.3 Adjustment Procedures

Generally when travel data comparisons are made, chances are that not all the comparisons will be satisfactory. Appropriate adjustment procedures have been developed and they are:

Method 1: If the reported trip data is under-reported by a fairly constant amount for each hour of the day, a uniform factor may be applied to all trips.

Method 2:   If the reported trips data indicate that peak-hour trips compare favorably and that the off-peak comparisons vary by a constant amount, then a uniform factor may be applied to all non-work trips.

Method 3:   This method uses adjusting factors by trip purpose. This is the recommended method when the screenline comparisons do not meet the criteria cited in the preceeding methods. The reasons for recommending this method are:

- Adjustment by purpose requires that the adjustor examine the data in detail

- This is the only method whereby the total percentage comparison and the comparison by hours can both be adjusted satisfactorialy

- Some trips are not reported as completely as some others. It is for example more likely to forget a non-work trip than a work trip.

The general procedure for applying any of the above three methods is to assume that the adjustment factor is applied only to internal trips. The rationale is that the external trips are fully reported because of higher sample rates. As an example, suppose the following trips have to be adjusted

Screenline count:	1000 trips	
Expanded O-D data:	540 internal trips	(60%)
	360 external trips	(40%)
	900 total trips	(100%)

Since we have only 900 trips from the O-D survey, we have a 90% screenline check, and we want to expand it to 100% screenline check. We know that:

external trips = 360, which is 35% with respect to screenline count, and

internal trips = 540, which is 54% with respect to screenline count,

so $36\% + F(54\%) = 100\%$

and $F = 1.18$

where F = Adjustment factor

The Federal Highway Administration has developed several computer programs to aid in the determination of the number and

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and type of trips crossing screenlines (See Bureau of Public Roads, 1970.)

When adjusting a screenline by trip purpose, again only internal auto driver trips are considered, and the following procedure is recommended:[*]

1. Obtain a tabulation of total auto driver trips crossing and not crossing the screenline by time and by purpose.

2. Determine the amount of under-reporting that exists in the internal auto driver trip data for trips crossing the screenline (U_{ic}).

   The value of U_{ic} is obtained as follows:

$$U_{ic} = \frac{T_{gc} - (T_{ic} + T_{ec})}{T_{ic}}$$

   where

   T_{gc} = total number of autos counted crossing the screenline

   T_{ic} = total number of internal autos crossing the screenline as determined from expanded trip inventories.

   T_{ec} = total number of external autos crossing the screenline as determined from the expanded trip inventories.

3. Examine the screenline comparison graphs to get a "feel" for what trips are under-reported. Develop adjustment factors by trip purposes such that a plot of screenline ground counts and adjusted survey data compare favorably.

4. Apply the adjustment factors to total internal auto driver trips crossing and not crossing the screenline. Set the adjust total equal to T_{ia}.

5. Determine the amount of area wide under-reporting that exists in the internal auto driver trip data (U_i) where

$$U_i = \frac{T_{ia} - T_{ir}}{T_{ir}}$$

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[*]Bureau of Public Roads. June, 1970. p. II-19.

and

T_{ir} = total number of internal auto driver trips reported

T_{ia} = total number of internal auto driver trips after adjustment

U_{ic} is different from U_i due to the difference between the screen-line and the total internal area with respect to the proportion of total trips made for each specific trip purpose. The total account of under-reporting of internal trip (U_i) will not be used in adjusting the data, but it is good to know the magnitude of under-reporting.

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CHAPTER VIII

TRIP TABLES

Once all the travel data have been checked and adjusted, trips can be summarized in trip tables. A trip table is a zone-to-zone matrix of trips. All the trips to or from these zones are assumed to end or begin at the center of activity of these zones. Trip tables do not contain specific routings between zone, rather they only provide information about trip interchanges for all the zones in the study area. A typical table is shown diagramatically in Figure 20.

There are two basic types of trip tables used in transportation:

1. Origin-destination (O-D) tables

2. Production and Attraction (P-A) tables

Trip-tables are sorted by origin zone in the O-D tables or by production z-nes in case of P-A tables (Figure 21).

The O-D trip tables consist of a matrix of trips from each zone (origin) to each other zone (destination). Generally, several trip tables are made depending upon the type of vehicle and purpose of the trip.

FIGURE 20. DIRECTIONAL TRIP TABLE

Traffic Zone

where

$$A_i = \sum_{j=1}^{n} a_{ji} \qquad \text{for } i = 1, 2, \ldots n \quad \text{and} \quad j \neq i$$

$$P_i = \sum_{j=1}^{n} a_{ij} \qquad \text{for } j = 1, 2, \ldots n \quad \text{and} \quad j \neq i$$

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FIGURE 21. TRIP INTERCHANGE TABLE
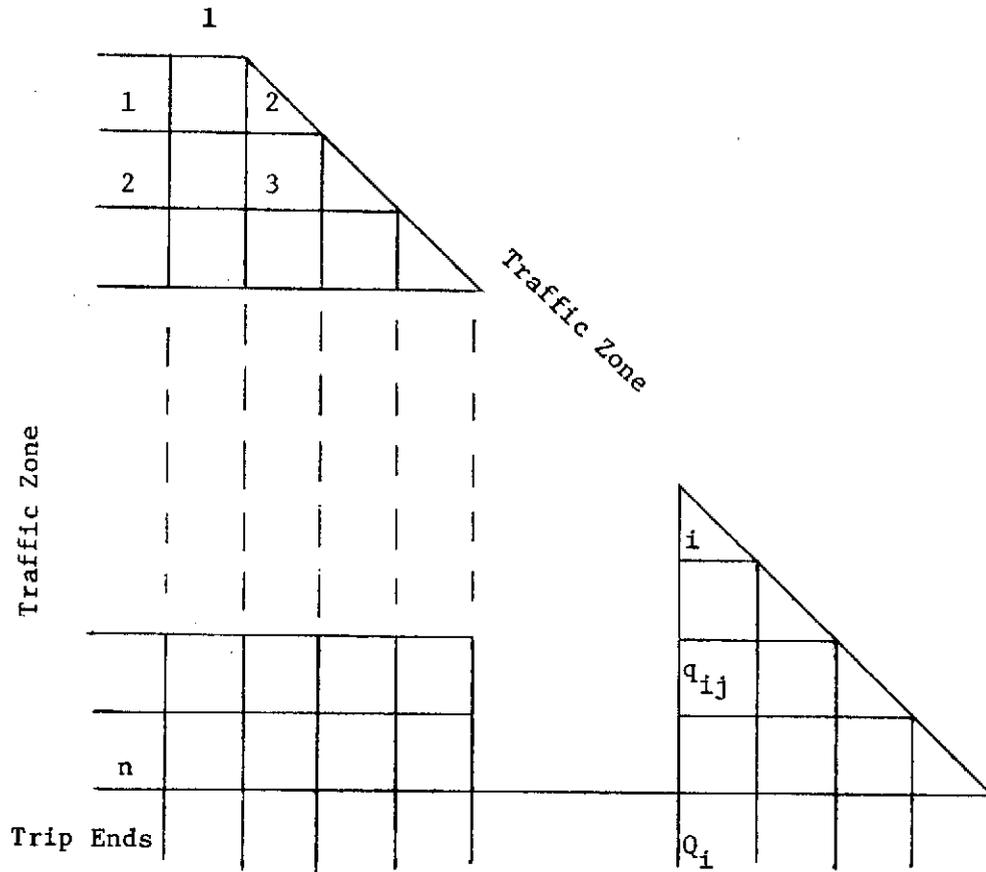
where

$$q_{ij} = a_{ij} + a_{ji}$$

q_{ij} = number of trip interchanges

$$Q_i = \sum_{j=i+1}^{n} q_{ij} \qquad (j > i)$$

The following schematic indicates possible O-D trip tables.

Origin-Destination   Vehicle Type   Purpose
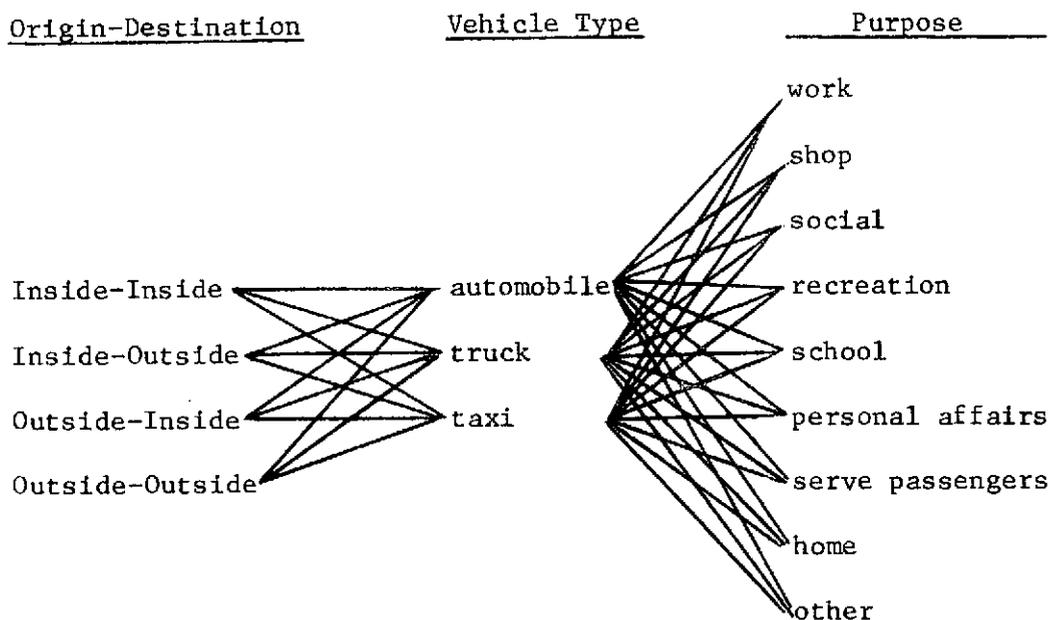
An assignment trip table summarizes all the different O-D tables into one table. O-D assignment trip tables are used as supplemental check for the data, and for the calibration of the traffic assignment network. In some instances when the effect of special trip generators on the network are being studied, an O-D table with only a portion of the above mentioned trip categories will be made. For example it is sometimes desirable to know the effect of external trips on a particular area or zone.

P-A trip tables are developed for further use in the mathematical distribution and generation models. In the P-A trip tables a trip origin is associated with a production and a trip destination with an attraction, with the following restrictions:

1. All trips that have an end at the home are considered to be the production (origin) end of the trip regardless of the direction the trip actually moves, and

2. For all non-home based trips the trip origin is associated with a production and trip destination is associated with an attraction.

Generally, about 80% of the trips of any urban transportation study are home based trips, i.e., with one end of the trip at the

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home. This makes the calibration of the gravity model much easier than if O-D trips were used. The following are typical home based trips:

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                          ,work
                        ,shopping
                      social-recreation
home<                 eat meal
                     medical/dental
                      other
```
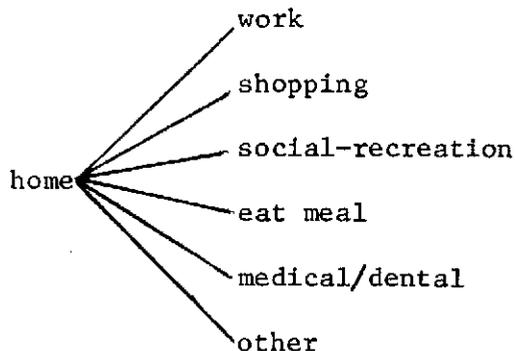
The degree of stratification of home based trips differs depending upon the size and overall objective of the particular transportation study.

8.1 From O-D Survey to Trip Tables

The task of summarizing and editing the O-D survey information into trip tables used to be a tedious and lengthy process. In recent years with the advent of computer technology, all the trip information gathered in the O-D surveys is coded on computer cards or tapes. This makes the sorting and editing of data much faster and more reliable. Generally, when the trip information is punched on computer cards the following nomenclature is used:

1. Dwelling Unit Information — Card Set No. 1
2. Persons Trips from Internal Survey — Card Set No. 2
3. External Trips — Card Set No. 3
4. Truck Survey Trips — Card Set No. 4
5. Taxi Survey Trips — Card Set No. 5

Each card besides having all the trip data has an expansion factor for each type of card depending upon the size of the sample taken during the survey.

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8.2 Type Linking

Linking is the process of giving trips their true desired origin and destinations. Because of the standard origin destination survey definition of a trip many journeys made by a trip maker have to be represented by two or more trip records even though only one journey is involved. In an origin destination survey, one trip ends and another begins every time a person changes his mode of travel, i.e., an automobile driver stops to serve a passenger, or when the trip maker reaches its ultimate destination.

There are two types of trips which require linking:

- Change in Mode
- Serve passenger

When these trip purposes are analyzed separately the relationship between the actual starting point, the ultimate destination and the true purpose of the trip are lost. Consequently, it is desirable to combine or link those trips with a "purpose to" or "purpose from" either change mode of travel or serve passenger so that the relationship between the purpose and the ultimate destination of the trips is preserved.

The following are some examples of trips that might be obtained through linking.[*]

- An auto driver driving his car to a transit station, where he boards a transit vehicle and rides to work. Since the ultimate purpose of this journey was to get from home to work, it is desirable to consider this trip to be a home-to-work trip by transit. The assumption is that if satisfactory transit were available at the trip-makers origin, he would have used it.

Recorded Trip

home →(auto driver)→ change of travel mode →(transit passenger)→ work

Linked Trip

home →(transit passenger)→ work

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[*]Bureau of Public Roads. June, 1970.

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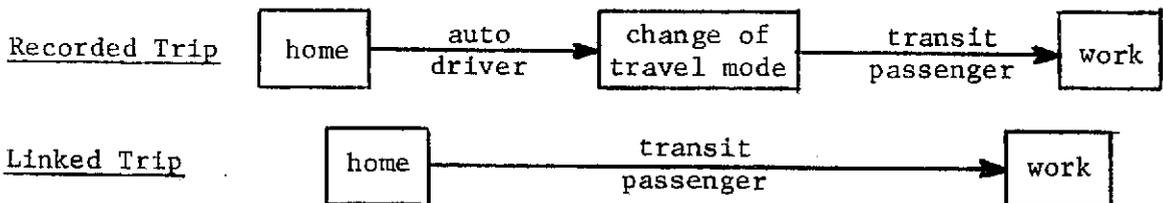
● An auto driver driving to work, stops first at the school where he leaves his child. There are three trips recorded in the home interview: (1) an auto driver trip to serve passenger; (2) an auto driver trip from serve passenger to work; and (3) an auto passenger from home to school trip. Since the ultimate purpose of the auto driver's trip was to get to work, his two trips are linked into one auto driver from home to work. The child's ultimate purpose was to go to school, thus his trip remains home to school auto passenger trip.

Recorded Trips
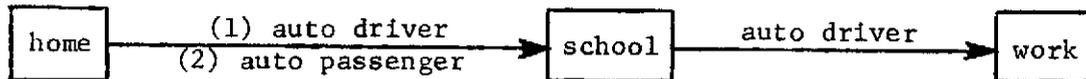
Linked Trips

The trip linking process causes a decrease in both the absolute number of trips taking place and in total vehicle miles of travel in the urban area. The loss of vehicle miles of travel results from the more direct routing of some linked trips. The decrease in the number of trips can be determined by simply subtracting the number of trips in the linked records from those in the unlinked records. The slight decrease in vehicle miles of travel can be obtained by assigning both the linked and the unlinked records to the study area network and subtracting the two resulting vehicle miles of travel.

After editing and linking trips, trip tables can be made, which will be used in the assignment model and in the regression analysis for trip generation.

CHAPTER IX

TRIP GENERATION

Trip generation is the process of developing and applying
relationships which related the number of trips produced and at-
tracted by an area to certain characteristics of the area.[*]

The focus on this relationship was one of the major contri-
butions of the Detroit study of 1953. Prior to this time travel
patterns were described directly from the O-D tables and by desire
lines describing schematically the traffic distribution. Forecasts
of future travel patterns were simply developed by inference from
past traffic growth curves. But from the early 1950's on, more and
more emphasis has been placed on analytical techniques in describing
trip productions/attractions and trip forecasting.

The basic philosophy behind trip generation is that it is
more reliable to forecast trips as a function of land use and socio-
economic related data than it is to forecast trips based on traffic
growth rates alone. The reason for this is because it is more re-
liable to forecast land uses and socio-economic data, and because
it is assumed that the relationship between travel patterns, land
use and socio-economic characteristics are stable with respect to
time.

Urban triffic patterns can be said to be a function of:[**]

● The pattern of land use in an area, including the lo-
cation and intensity of use

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[*] Federal Highway Administration, 1972

[**] Bureau of Public Roads, June, 1967. p. 2

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- The various social and economic characteristics of the population of an area

- The type and extent of the transportation facility available in an area

Different types of land uses and/or socio-economic conditions generate different types and number of trips. As it has been shown previously, a common breakdown of trips by purpose for medium to small traffic studies would generally lead to three purposes of trips: (1) home based work trips; (2) other home based trips; and (3) non-home based trips. The following entities show a general relationship between the three above mentioned types of trips and relevant land-use and socio-economic variables that would explain the behavior of these trips.

1. HBW - (home based work trips)

   HBW productions = f (D.U., automobiles/D.U., labor forces, etc.)

   HBW attractions = f (total employment)

2. OHB - (other home based trips)

   OHB productions = f (D.U., automobiles/D.U., economic level, population)

   OHB attractions = f (Retail employment, public and institutional employment, population, professional service employment)

3. NHB - (non-home based trips)

   NHB productions = f (Retail employment, retail sales, office uses, public institutional uses)

   NHB attractions = f (NHB production)

For the most part, the trips serving as the dependent variables are vehicle trips (by purpose). In cities having (large studies) a mass transit system, we would collect data on person trips in order to facilitate the development of a modal split model.

Typical trip generation and attraction analysis involves either:

- A rate analysis

- A cross-classifications analysis

- Regression analysis

9.1 Rate Analysis

9.1.1 Land Area Trip Rate Analysis

This procedure deals directly with land areas and has as its objective the establishment of trip rates which reflect the character, location, and intensity of the land use. Character is inherent in the land use categories. Location, by definition, considers the spatial distribution of the analysis units. Most often trip rates are developed for areal units of similar density, thus accounting for the intensity factor.

Intensity of land use expresses the amount of an activity or characteristic to be found in a given areal unit and it is usually stated in terms of density variables such as D.U./Acre. Variations in intensity have a distinct impact on the number and type of trips generated within the study area (see Figures 22 and 23).

The character of the land use reflects the socio-economic identify of the analysis unit. Two variables associated with residential land use that are indices of character are family income and car ownership. The contribution of a variable describing character should be evident. Families in the higher income range are often multi-car families which results in increased mobility. Low income families often own no cars and must rely on public transportation, thus generating fewer automobile trips. Higher income families exhibit an increased amount of travel from home for purposes other than work, typically for shopping and social-recreation purposes*
see Figures 24 and 25).

The location of the land use activity refers to the spatial distribution of land uses and land use activities. The location of

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*Bureau of Public Roads. June, 1967. pp. 8-12
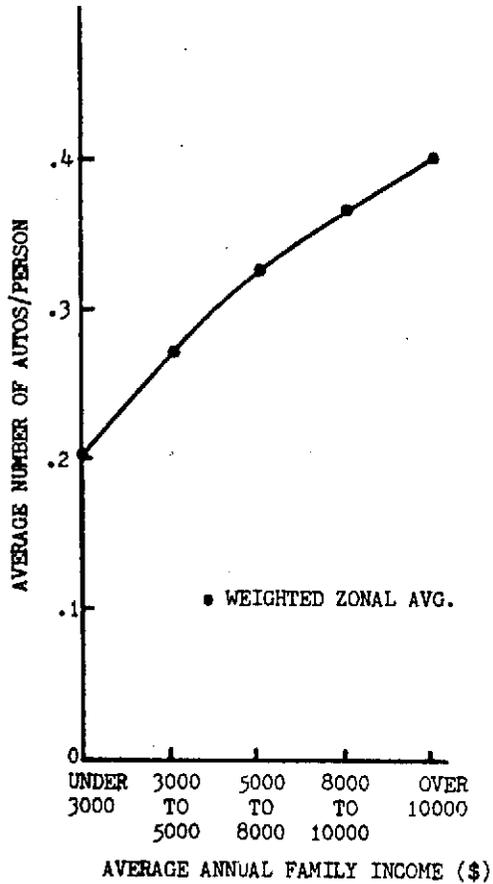
FIGURE 22.   THE EFFECT OF INCOME
ON AUTOMOBILE
OWNERSHIP
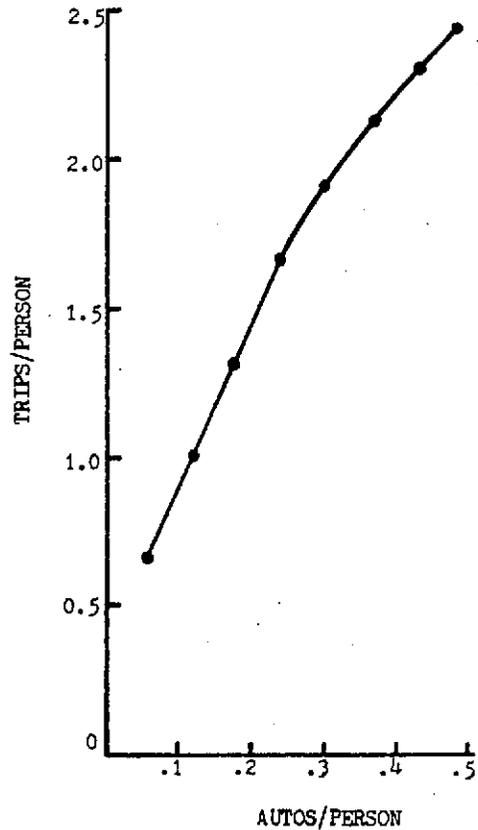
FIGURE 23.   THE EFFECT OF
AUTOMOBILE OWNERSHIP
ON TRIPMAKING

(from: Bureau of Public Roads, 1967)
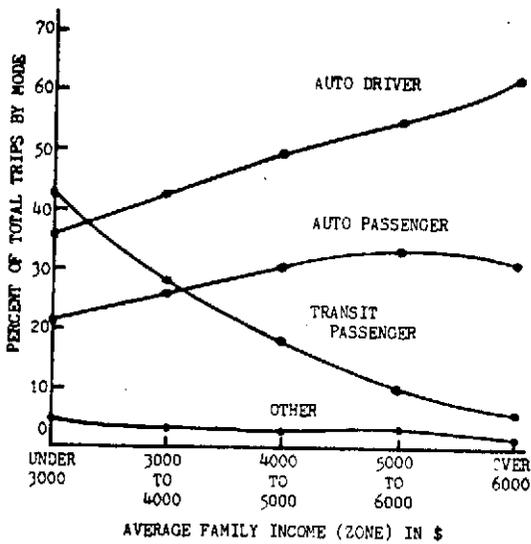
FIGURE 24.   THE EFFECT OF
INCOME ON TRAVEL
MODE
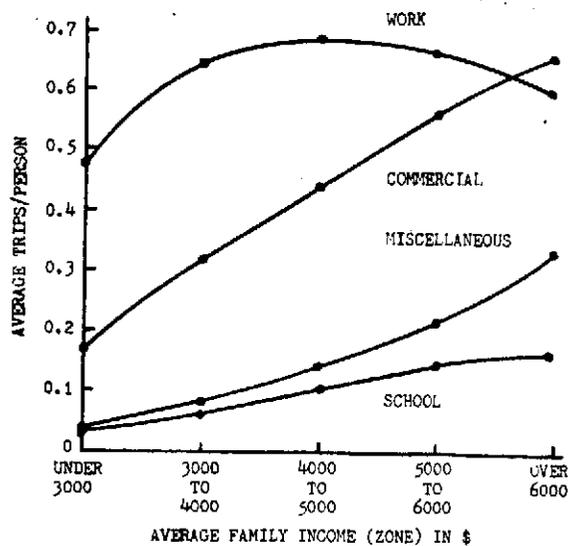
FIGURE 25.   THE EFFECT OF INCOME
ON TRIP RATES BY
PURPOSE

(from: Bureau of Public Roads, 1967)

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residential land use activities in many instances has a significant effect on trip generation. This factor is commonly manifested in the measures of intensity and character. In general, data collected in the land use survey are related to data collected in the origin-destination survey to establish a trip generation rate (Table 15).

TABLE 15

EXAMPLE RELATIONSHIP BETWEEN LAND USE
TYPE AND TRIP RATE

Land Use Type	Land Use Survey Acres	O-D Survey Trips-ends	Rate Trip-ends/Acre
Residential	2,000	4,000	2
Industrial	200	3,000	15
Commercial	50	2,000	40

(from Bureau of Public Roads, 1967)

9.1.1.1 Average of Ratios

The "average of ratios" is determined by first calculating the trip generation rate for each individual zone and then averaging the individual rates. In this procedure small zones are weighted equally with large zones regardless of the zone size.

$$b_{ar} = \frac{\sum_{i=1}^{n} \frac{Y_i}{x_i}}{n}$$

where x_i = independent variable (socio-economic)

Y_i = dependent variable (trips)

n = number of zones

9.1.1.2 Ratio of Averages

For the "ratio of averages" the rate is taken simply as the ratio of the the total number of trips for all zones to the total number of units of independent variables for all zones.

$$b_{ra} = \frac{\sum\limits_{i=1}^{n} Y_i}{\sum\limits_{i=1}^{n} x_i}$$

where x_i = independent variable

Y_i = dependent variable, trips

n = number of zones

9.1.1.3 Quartile Rates

All zones are ranked in order of increasing value of the individual zone rates. This ranked set of zones is then divided into quartiles and the ratio of the average for each quartile is computed. Trips for each zone using the proper quartile rate are then calculated.

$$\text{Total number of rates} = \frac{Y_1}{x_1}, \frac{Y_2}{x_2}, \ldots, \frac{Y_n}{x_n}$$

and suppose they are arranged in increasing order of values, i.e.,

$$\frac{Y_1}{x_1} \leq \frac{Y_2}{x_2} \leq \frac{Y_3}{x_3} \leq \ldots, \leq \frac{Y_n}{x_n}$$

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then rates for

$$\text{Quartile } 1 = \frac{\sum\limits_{i=1}^{k} Y_i}{\sum\limits_{i=1}^{k} x_i} \qquad\qquad \text{Quartile } 3 = \frac{\sum\limits_{\ell+1}^{m} Y_i}{\sum\limits_{\ell+1}^{m} x_i}$$

$$\text{Quartile } 2 = \frac{\sum\limits_{i=k+1}^{\ell} Y_i}{\sum\limits_{i=k+1}^{\ell} x_i} \qquad\qquad \text{Quartile } 4 = \frac{\sum\limits_{m+1}^{n} Y_i}{\sum\limits_{m+1}^{n} x_i}$$

where $\dfrac{n}{4} = K;$

$2K = \ell;$

$3K = m$

9.1.2 Cross Classification Analysis

Cross classification is a technique in which the change in one variable (dependent) can be measured when the changes in two or more other variables are accounted for. Cross classification is referred to as a "nonparametric" or distribution-free technique, since it does not rely heavily on an assumed distribution of the data.

Essentially, for cross classification analysis, a multidimensional matrix is constructed, each dimension representing independent variables. These characteristics are then stratified into meaningful categories. Each dwelling unit observation is allocated to a cell of the matrix based on the categories of the independent variables. The dependent variable (trips of some type) is accumulated cell by cell and the average for each cell is determined.

The objective of this procedure is to cross-classify basic dwelling unit data into relatively homogeneous sub-groups and then determine the mean rate for each of the sub-groups. Table 16 shows the relationship to average total person trips per dwelling unit.

TABLE 16

RELATIONSHIP OF FAMILY SIZE AND AUTO OWNERSHIP TO
AVERAGE TOTAL TRIPS PER DWELLING UNIT

Number of Persons/D.U.	Average total person trips/D.U.				
	Number of autos owned/D.U.				
	0	1	2	3 & over	Weighted Average
1	1.03	2.63	4.37	---	1.72
2	1.52	5.13	7.04	2.00	4.38
3	3.08	7.16	9.26	10.47	7.46
4	3.16	7.98	11.56	12.75	9.10
5	3.46	8.54	12.56	17.73	10.16
6-7	7.11	9.82	9.61	16.77	11.00
8 & over	7.00	9.65	6.18	27.00	12.24
Weighted Avg.	1.60	6.62	10.53	13.68	6.48

(from Bureau of Public Roads, 1967)

9.2 Regression Analysis

As mentioned earlier, certain types of land use and socio-economic data are easily correlated with existing trip ends. The regression analysis determines the relationship between an array of dependent and independent variables, establishing a line of "best fit" by calculating the equation of the line by the method

of "least squares" (Appendix I). The basic equation has the following form:

$$Y = b_o + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n ,$$

where

Y = production or attraction trip ends (dependent variable),

b_o = constant (to be determined),

b_i = coefficients to be determined, and
$i = 1, 2, 3, \ldots, n$

x_i = socio-economic and land use parameters (independent variables) and
$i = 1, 2, 3, \ldots, n$

When developing regression equations, a major item in the evaluation and acceptance of the regression equation is logic and the existence of a casual relationship between independent socio-economic and dependent variables (trips). Many times a regression equation can satisfy all of the statistical requirements but still not be acceptable because of the illogical relationships between dependent and independent variables. Some typical regression equations are as follows:[*]

HBW productions

$Y = 3.6 + 0.67$ (No. of cars) $- 0.99$ [total population]
$+ 0.064$ [total labor force]

HBW attractions

$Y = 22.6 + 0.79$ [employment @ work end] $+ 0.80$ [acres in commercial use] $+ 1.7$ [acres in office use]

---

[*]Waco (Tex.) Transportation Study, 1956

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According to Jefferies and Carter (1968) there are certain assumptions concerning the data used in a least square analysis:

1. The data used for developing the production and/or attraction should be

   • easily obtained

   • capable of explaining trip generation characteristics

   • reflect the influence of the change in the independent parameters on trip generation rates

2. Reliable and inexpensive methods should be available for forecasting the data used as independent variables to the design year.

3. The final trip-generation equation should be easy to use and should contain as few variables as possible consistent with the required accuracy.

4. The values of the independent variables (x_i) are fixed and can be measured without error.

5. For a given value of the independent variable, the values of the dependent variable must be normally and independent distributed about the mean of the dependent variable for the given value of the independent variable.

6. The variance of the dependent variable is the same for all values of the independent variable.

CHAPTER X

TRIP DISTRIBUTION MODELS

Trip distribution analysis is the process by which trips
of every triffic zone are distributed to every other traffic zone
in the study area.   Trip distribution models have evolved from
very crude empirical models to models relying basically on growth
factors to the more sophisticated and recent mathematical models.
The best known distribution models are:

1.   Fratar (successive approximation)

2.   Gravity model

3.   The intervening opportunity model

4.   The competing opportunity model

5.   Linear programming transportation model

10.1 Gravity Model

In this section we will focus on the gravity model which
is one of the best known and most widely used of the distribution
models.   For a general description of the other four models, refer
to Appendix B.

The gravity model was introduced as a potential traffic
distribution model by Voorhees in 1955.   As the name implies, this
model is based on Newton's principles of universal gravitation,
which stated that every particle in the universe attracts every
other particle with a gravitational force according to the
following formula:

$$F = G \ \frac{m_1 \ m_2}{R^2}$$

where

> F = Gravitational force
>
> G = Gravitational Constant
>
> m_1, m_2 = Mass of bodies 1 and 2
>
> R = Distance between 1 and 2

Similarly, the gravity model as applied to trip interchanges in a transportation network is based on the premise that the number of trips between two zones i and j is directly proportional to a measure of the attraction of zone j, A_j, and inversely proportional to the spatial separation, time elapsed, cost, or any other impedance factor between zones i and j, d_{ij}.

The gravity model can be stated mathematically (Bureau of Public Roads 1968):

$$T_{ij} = P_i \frac{\dfrac{A_j}{d_{i,j}^b}}{\dfrac{A_1}{d_{i,1}^b} + \dfrac{A_2}{d_{i,2}^b} + \dfrac{A_n}{d_{i,n}^b}} \qquad (1\text{-}10)$$

$$T_{ij} = P_i \frac{\dfrac{A_j}{d_{ij}^b}}{\sum_{k=1}^{n} \dfrac{A_k}{d_{i,k}^b}} \qquad (2\text{-}10)$$

where

> i = 1, 2, 3, . . . , n
>
> T_{ij} = number of trips produced at zone i and attracted to zone j
>
> P_i = total trips produced by zone i (by purpose)

A_j = total trips attracted by zone j (by purpose)

d_{ij} = measure of spatial separation between zones i and j

b = empirically determined exponent (constant)

The exponent b is the only parameter affecting the distribution. When the value of the exponent is large, trip flows tend to be a function of the spatial separation, a smaller value on b gives greater weight to the relative attraction factors of the zones of destination. In the extreme, a zero exponent would allow trips to be distributed in direct proportion to the attraction of the zones of destination. The exponent b varies with trip purpose and particular urban areas. As a broad generalization when d_{ij} is expressed in travel time the exponent tends to be about 1.0 for work trips, 2.0 for shopping trips, and 3.0 for social trips (Figure 26).

Equation 2-10 could be expressed as follows:[*]

$$T_{ij} \propto P_i \, A_j \, F_{ij} \, K_{ij} \qquad (3\text{-}10)$$

where

T_{ij} = Trips produced at i and attracted to j

P_i = Total trips produced at i

A_j = Total trips attracted at j

F_{ij} = Friction factor for interchange i-j

K_{ij} = Socio-economic adjustment factor for interchange i-j (if needed)

i = An origin zone number = 1, 2, 3, . . . , n, and

n = Total number of zones

Relation 3-10 can be written as an equation by introducing a constant c.

$$T_{ij} = C \, P_i \, A_j \, F_{ij} \, K_{ij} \qquad (4\text{-}10)$$

---

[*]Bureau of Public Roads. June 1970.
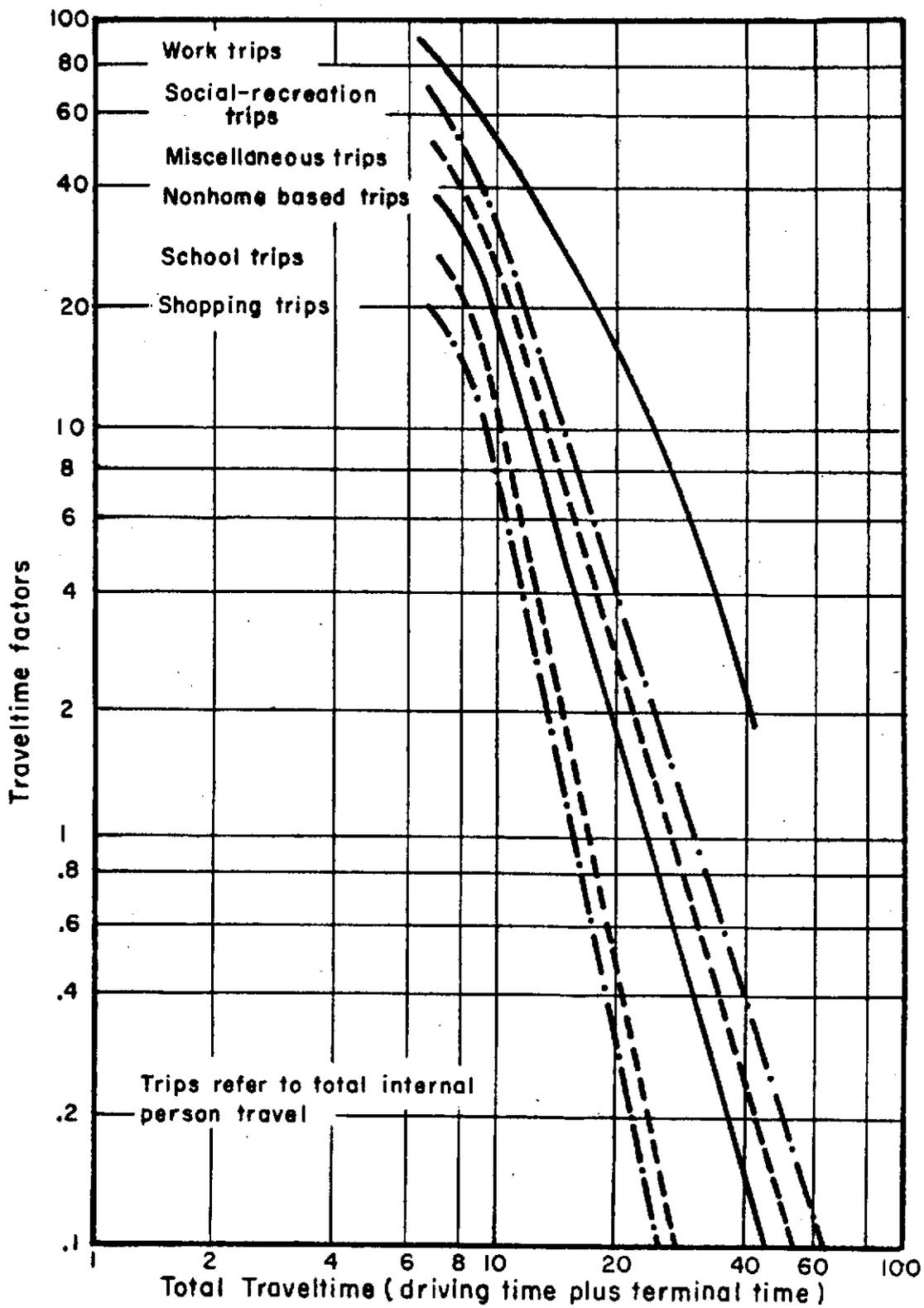
FIGURE 26. TRAVELTIME FACTORS FOR WASHINGTON, D.C., 1955
(from Bureau of Public Roads, 1968)

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A specific value for constant C can be found for any zone i, if it is specified that the sum of all T_{ij}'s for any origin zone i is equal to P_i, i.e., total production at zone i.

Given

$$P_i = \sum_{j=1}^{n} T_{ij}, \text{ and} \qquad\qquad (5\text{-}10)$$

substituting Equation 5-10 into Equation 4-10,

$$P_i = \sum_{j=1}^{n} T_{ij} = \sum_{j=1}^{n} \left[C_i\, P_i\, A_j\, F_{ij} K_{ij} \right]$$

$$P_i = C_i\, P_i \sum_{j=1}^{n} \left[A_j\, F_{ij}\, K_{ij} \right] \text{ and}$$

dividing both sides by P_i, we obtain

$$1 = C_i \sum_{j=1}^{n} \left[A_j\, F_{ij}\, K_{ij} \right]$$

and

$$C_i = \frac{1}{\displaystyle\sum_{j=1}^{n} \left[A_j\, F_{ij}\, K_{ij} \right]} \qquad\qquad (6\text{-}10)$$

substituting Equation 6-10 into Equation 4-10 gives

$$T_{ij} = P_i\, \frac{A_j\, F_{ij}\, K_{ij}}{\displaystyle\sum_{j=1}^{n} \left[A_j\, F_{ij}\, K_{ij} \right]} \quad \text{for } i = 1, 2, 3, \ldots, n \quad (7\text{-}10)$$

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Equation 7-10 is the standard gravity model formula. This more sophisticated formulation has enough free parameters to fit the data to almost any degree of accuracy desired. Parameters P_i and A_j are concerned with land use and socio-economic characteristics. A third parameter, t_{ij} travel time, is incorporated with the effect of area-wide spatial separation of trip interchange between zones to produce the fourth factor F_{ij}, friction factor or travel time factor. The fifth factor, K_{ij}, is the zone to zone adjustment factor which accounts for social and economic considerations not otherwise considered. (Special generator, schools, hospitals, etc.)

The data needed to determine these parameters are the O-D survey, travel time facilities, inventory and socio-economic survey. Once all the necessary parameters have been determined, the model can be calibrated. The following is an outline of the calibration process.[*] (Since some of those procedures have been explained in previous sections, refer to those sections for more detailed information.)

    A. Preparing basic data

        1. Editing trip records
        2. Sorting trip records
        3. Linking trip records
        4. Selecting trip records
        5. Determining spatial separation between zones
           • Preparing the network
           • Determining interzonal driving time
           • Determining travel times

    B. Analysis of basic data

        1. Building tables of zone-to-zone movements
        2. Obtaining a trip length frequency distribution

    C. Developing travel time factors

        1. Selecting initial travel time factors
        2. Calibration to obtain final travel time factors

    D. Topographical barriers

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[*]Bureau of Public Roads, 1968

E. Developing zone-to-zone adjustment factors

    1. Attraction factors A_j's

    2. Socio-economic factors K_{ij}'s

10.2 Gravity Model Calibration

10.2.1 Preparing Basic Data

(Refer to Chapter V)

10.2.2 Analysis of Basic Data

(Refer to Chapter VII)

10.2.3 Developing Traveltime Factors

10.2.3.1 Selecting Initial Traveltime Factors[*]

Because of the lack of a specific mathematical function
which can express the effect of spatial separation between zones,
it is necessary to go through a trial and error process to fit the
model to a particular urban travel condition. Presently there are
two methods by which an initial set of travel time can be obtained.

    1. Assume each travel time factor equal to 1 which means
travel time has no effect on trip interchange.

    2. Assume travel times factors from a similar trans-
portation study. This method is preferable to
method (a) because generally it requires less cali-
bration. Table 17 shows travel time factors used in
the New Orleans, La., Transportation Study.

10.2.3.3 Calibration to Obtain Final Traveltime Factors[*]

Once an initial set of traveltime factors have been obtained,
it is possible to calculate trip interchanges using the gravity
model. Input for this process is:

    1. Trip production and attractions by zone and by purpose
of trip.

    2. Initial travel time factors for each increment of
travel time.

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[*]Bureau of Public Roads, 1968.

TABLE 17

TRAVELTIME FACTORS IN THE NEW ORLEANS, LA., TRANSPORTATION STUDY

Minutes Traveltime	Home to Work	Home to Shop	Home to Soc.-Rec.	Home to School	Home to Other	NHB
1	1,450	7,200	7,800	4,300	6,800	5,100
2	1,150	7,000	1,150	5,600	5,100	3,400
3	740	4,600	2,500	1,500	3,400	1,700
4	540	2,800	1,390	840	1,700	950
5	430	1,300	840	550	880	530
6	345	700	650	390	530	330
7	285	420	400	290	340	220
8	240	250	305	230	237	150
9	198	170	240	190	168	110
10	170	120	190	155	123	81
11	149	82	159	130	92	63
12	126	61	130	110	72	51
13	110	46	110	94	58	40
14	97	36	91	80	48	33
15	86	27	80	74	38	27
16	77	23	70	64	32	23
17	69	18	60	57	27	20
18	62	15	54	50	23	17
19	56	12	48	46	20	15
20	50	10	42	43	18	13
21	45	9	39	39	15	11
22	42	8	35	35	13	10
23	38	7	32	33	12	9
24	35	6	29	30	10	8
25	32	5	26	28	9	7
26	29	4	24	25	8	6
27	27	4	23	24	7	6
28	25	3	21	22	7	6
29	23	3	20	21	6	5
30	21	3	18	20	6	5
31	19	3	17	19	5	4
32	18	2	16	17	5	4
33	17	1	15	17	4	4
34	16		14	16	4	3
35	15		13	15	4	3
36	14		13	14	4	3
37	13		12	13	3	3
38	12		12	12	3	2
39	11		11	11	3	2
40	10		10	10	3	2
42	9		9	9	2	2
43	8		8	7	2	1
45	7		8	5	1	1
47	6		7	3		
50	5		6	2		
52	4		6	1		
56	3		5			
62	2		4			
71	1		3			
73			2			
78			1			

(from Bureau of Public Roads, 1968)

3. Minimum path traveltimes for all zones (from assign-
    ment model).

The output of this process after each itineration is:

1. A table of zone-to-zone trips as estimated by the
    gravity model.

2. A trip length frequency distribution by travel time
    increments for trip interchanges estimated by the
    gravity model.

3. A table of accessibility indexes (denominator of gravity
    model formula) for each zone.

4. A table of comparison between the trips send ($\sum_{i=1}^{n} T_{ij}$)
    to each zone by the gravity model and the trip attrac-
    tions (A_j) at each zone.

The trip length frequency distributions are the most useful of the
gravity model's outputs for calibration purposes. The percentages
of total trips for each trip purpose are plotted on rectangular
coordinate paper along with the O-D trip length frequency for each
trip purpose. Figure 27 shows the estimated and the survey trip
length frequency curve for one type of trip purpose. Since the
gravity model uses data directly from the field surveys to express
all parameters except the travel time factors, any difference be-
tween the two trip length frequency curves are due primarily to
the initial values of the travel time factors. Comparisons made
between O-D surveys curves and the gravity model curves are based
on the following criteria:

1. Both curves should be relatively close to one another
    when compared visually.

2. The difference between average trip lengths should be
    between $\pm$ 3%.

If the comparisons do not meet these criteria, another itineration
with some new travel time factors should be made. Mathematically
the iterative adjustment procedure for travel time factors is as
follows:

$$F_{adj} = F_{used} \frac{\text{O-D\%}}{\text{G-M\%}}$$

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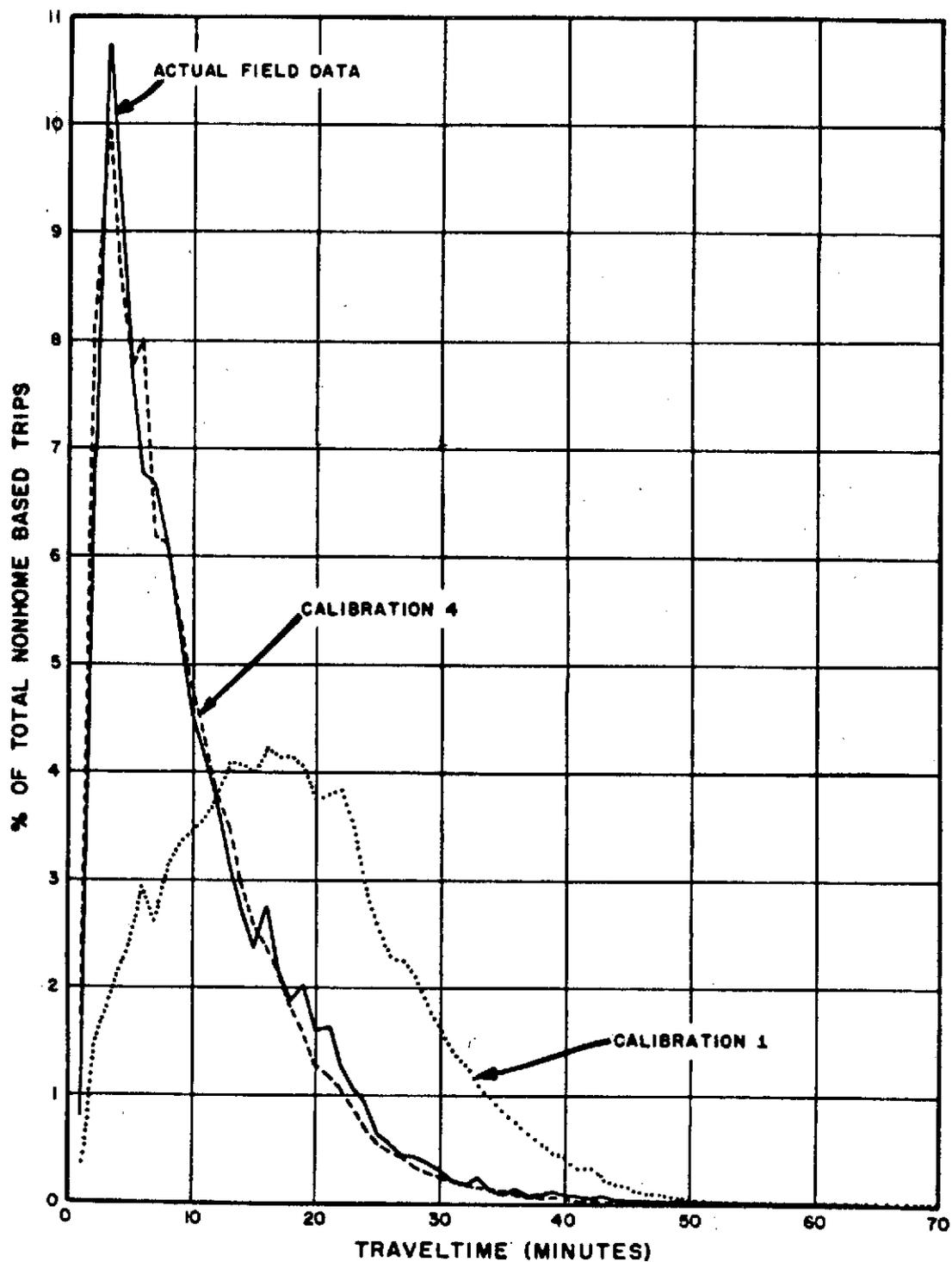
FIGURE 27. TRIP LENGTH FREQUENCY FOR NON-HOME BASED
TRIPS, WASHINGTON, D. C., 1955
(from Bureau of Public Roads, 1968)

where

F_{adj} = Travel time factor for next calibration

F_{used} = Travel time factor used in gravity model run

being analyzed

O-D% = % of origin-destination survey trips

G-M% = % of gravity model trips from run being analyzed

This calculation results in the adjusted travel time factor for each one minute increment of travel time.

The adjusted travel time factors are then plotted vs. their respective travel time increments on a log-graph paper (Figure 28). An analysis of some of these plots will generally indicate that for certain points the adjusted travel time factors do not reflect the gravity model theory. Table 18 shows for example, that trips which are seven minutes long have a travel time factor equal to 119, while the travel time factor for trips 8 minutes long is equal to 126 which is contrary to the gravity model theory. To adjust such discrepancies, "a line of best fit" (See Appendix I) is fitted to the distribution points. This line should be as smooth and as straight as possible. The line shown in Figure 28 meets these criteria. Once the line of best fit has been drawn, a new set of travel time factors is selected from it. At this point a new iteration for the model calibration can be made. Generally the maximum number of iterations required to obtain an adequate trip length frequency curve does not exceed three.

10.2.4 Topographical Barriers

Many of the gravity model studies conducted to date have shown that topographical barriers, such as mountains, rivers, and large open spaces may cause some bias in the gravity model trip interchange estimates. Studies in Washington, D. C., New Orleans, La., and Hartford, Conn., have shown such findings. For more detail refer to those studies.

TABLE 18

TRAVELTIME FACTOR ADJUSTMENT PROCEDURE

| (1) Traveltime	(2) % Trips (Actual)	(3) Traveltime factor # 1	(4) % Trips (Est. #1)	$\frac{(2)}{(4)} \times (3)$ (5) Adjusted traveltime factor	(6) Traveltime factor #2
1	0	0	0	0	0
2	0	0	0	0	0
3	1.508	172	1.165	223	300
4	1.477	162	0.970	247	247
5	3.529	152	2.607	206	206
6	6.954	142	5.616	176	176
7	9.110	132	10.135	119	145
8	14.798	122	14.379	126	126
9	13.381	112	14.725	102	110
10	13.234	102	13.410	101	101
11	12.801	92	13.032	90	90
12	7.716	82	8.342	76	76
13	7.030	72	7.496	68	65
14	4.057	62	4.479	56	56
15	1.635	52	1.840	46	46
16	1.016	42	0.934	46	40
17	1.754	32	0.791	71	32
18	0	0	0.060	0	0
19	0	0	0.020	0	0
20	0	0	0	0	0

(from Bureau of Public Roads, 1968)
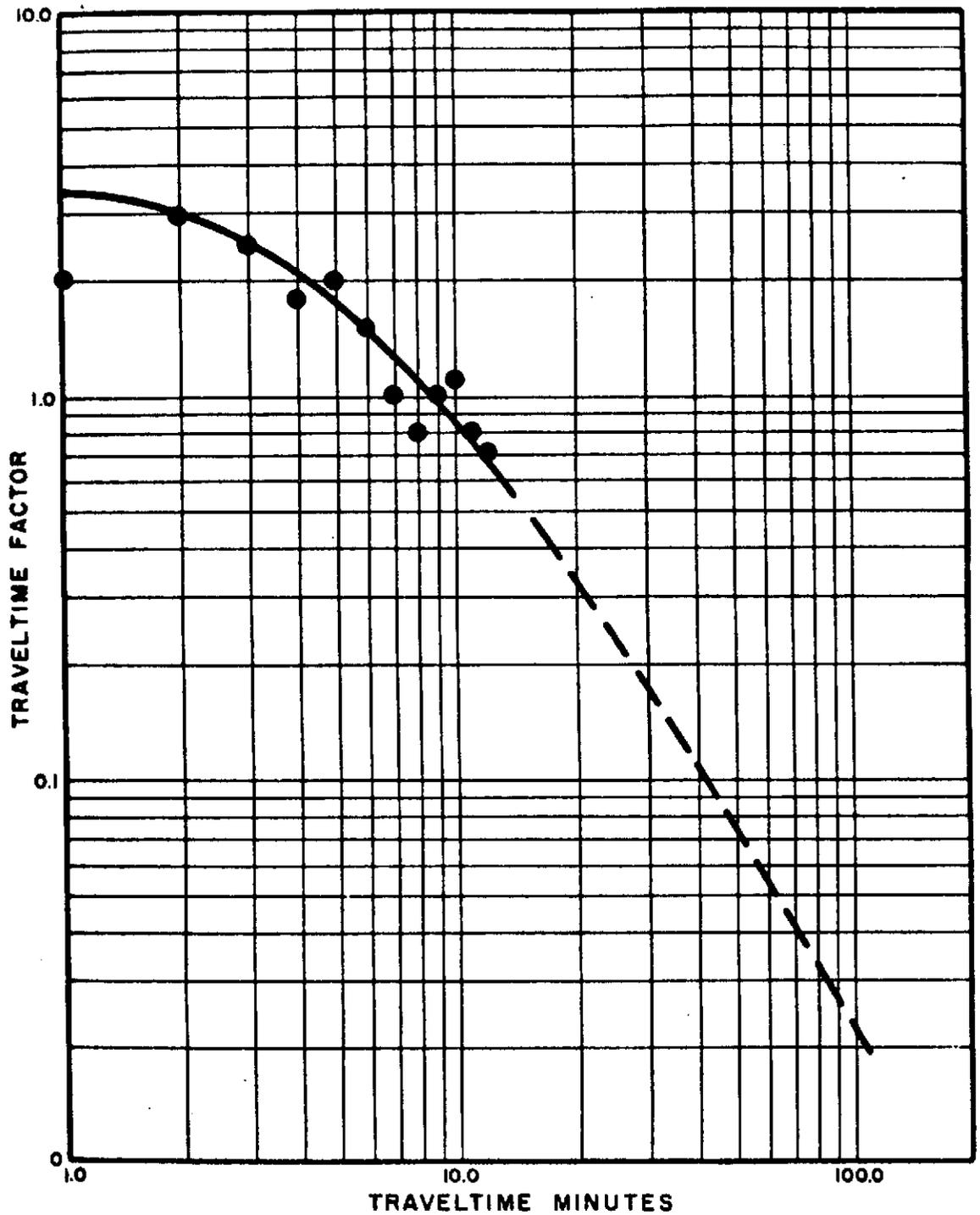
FIGURE 28. TRAVELTIME FACTORS VS. TRAVELTIME
(from Bureau of Public Roads, 1968)

10.2.5 Developing Zone-to-Zone Adjustment Factors

Generally there are other factors than those related to travel time which could affect patterns of urban travel, such as attraction factors and socio-economic conditions.

10.2.5.1 Attraction Factors

An iterative procedure is used to refine calculated interchanges until actual attraction totals closely match the desired results. After each iteration, adjusted attraction factors are calculated according to the following formula:[*]

$$A_j{'} = A_j \frac{A_{uj}}{A_{oj}}$$

$A_j{'}$ = Attraction factor for next iteration

A_j = Attraction factor desired

A_{oj} = Attraction factor obtained in previous iteration

A_{uj} = Attraction factor used in previous iteration

10.2.5.2 Socio-Economic Factors

The effect of social and economic factors can be accounted for in the gravity model formula by the use of zone-to-zone adjustment factor, K_{ij}. Due to limited research on this particular point, the underlying reasons behind the need for K_{ij} factors is not well understood. However, several studies have indicated that the following may influence our ability to identify the real causes for the need to incorporate zone-to-zone adjustment factors into the gravity model:

1. The trip purpose stratification used today may not be precise enough to account for all the basic differences in travel patterns.

2. It is customary to develop a set of travel time factors

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[*] Bureau of Public Roads, 1970.

for each trip purpose category. Since trips between all zones are used in developing these factors, they represent the average area wide effect of travel time on trip interchange.

3. There is some evidence that factors such as income and residential density may influence the need for zone-to-zone adjustment. It is not yet clear whether these two factors may actually be a reflection of Items 1 and 2 or whether they are independent factors in themselves.

In conclusion it may be said that the zone-to-zone adjustment factors are obtained empirically and they reflect all of the "unexplainable factors" affecting the trip interchange between zones. In general, a procedure for adjusting socio-economic factors would depend on the ratio of the origin-destination survey results to the gravity model results for a particular movement, and to a magnitude of trips attracted to any zone which "needs" to be adjusted. This can be expressed mathematically as follows:[*]

$$K_{ij} = R_{ij} \frac{1 - X_i}{1 - X_i R_{ij}}$$

where

K_{ij} = Adjustment factor to be applied to movement between zone i and zone j.

R_{ij} = Ratio of 0-D survey results to the gravity model results for the movement between zone i and zone j.

X_i = Ratio of 0-D trips from zone i to zone j to total 0-D trips leaving zone i.

_____

[*]Bureau of Public Roads, 1968.

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CHAPTER XI

TRAFFIC ASSIGNMENT

Traffic assignment is accomplished by assigning to a path or family of paths the trips that occur between zonal pairs. The paths represent the most logical routes that drivers would take between the zone pair according to either:

1. Shortest distance

2. Shortest travel time

3. Least number of stops and turns

4. Minimum amount of pedestrian interference

5. Any combinations of the above

When all trip interchanges between centroids (zones) are assigned to the transportation network, the total number of trips assigned to these minimum paths can be obtained. The result is a representation of how traffic would distribute itself over a particular network during the time frame the trip table encompasses.[*]

The determination of minimum paths between centroids is a difficult and very time consuming task if done manually. Today, almost all traffic assignments are done by computers. Therefore the following general description of the traffic assignment procedure is presented considering computer utilization.

Inputs to the traffic assignment process are:

● A complete description of the transportation network

● A trip volume matrix of the interzonal traffic movement.

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[*]Federal Highway Administration. September, 1972.

11.1 Description of Transportation Network

From the inventory and survey of the existing street and highway network, a map is prepared which describes the components of the transportation system. Generally the geographical location and configuration of the transportation zones are superimposed on this map. Once this is accomplished, the whole transportation network is ready to be coded for computer utilization.

All traffic zones are represented by nodes or dots, called centroids. Centroids can be located anywhere inside a particular zone. A centroid can be defined as that point in a zone which is used to load all trips to and from that zone and represents the centroid of land use activity within the zone.

The street network in itself is coded by means of nodes and links. Generally all streets carrying a substantial volume of traffic should be included, i.e., freeways, arterials and collectors. Local streets inside the traffic zones are simulated by connections between zone centroids and the network. The assignment procedure does not assign intrazonal trips since all trips are loaded to and from a single point (centroid). In any size city, a general rule for network selection is to include all streets that are protected by signals or stop signs, but the ultimate criterion in network selection is judgment and general knowledge of the area. Nodes are also placed at each intersection in the network. Any segment of the network defined between two nodes is called a link. Nodes, called stations, are also inserted wherever a link crosses a cordon line and sometimes when a link changes direction.

One of the limitations of assigning traffic by computer is that each node has a limit as to the number of links emanating from it. Generally there are no more than four links per node, but this is not a real problem for multi-link nodes as is shown in the following illustration. Suppose that the maximum number of links per node in a traffic assignment procedure is four, and that there is a six-leg intersection in the network. In such a case the six street inter-

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section could be represented by two nodes linked by a "zero time and distance link." Figure 29 shows the procedure.

Actual Network

Coded Network
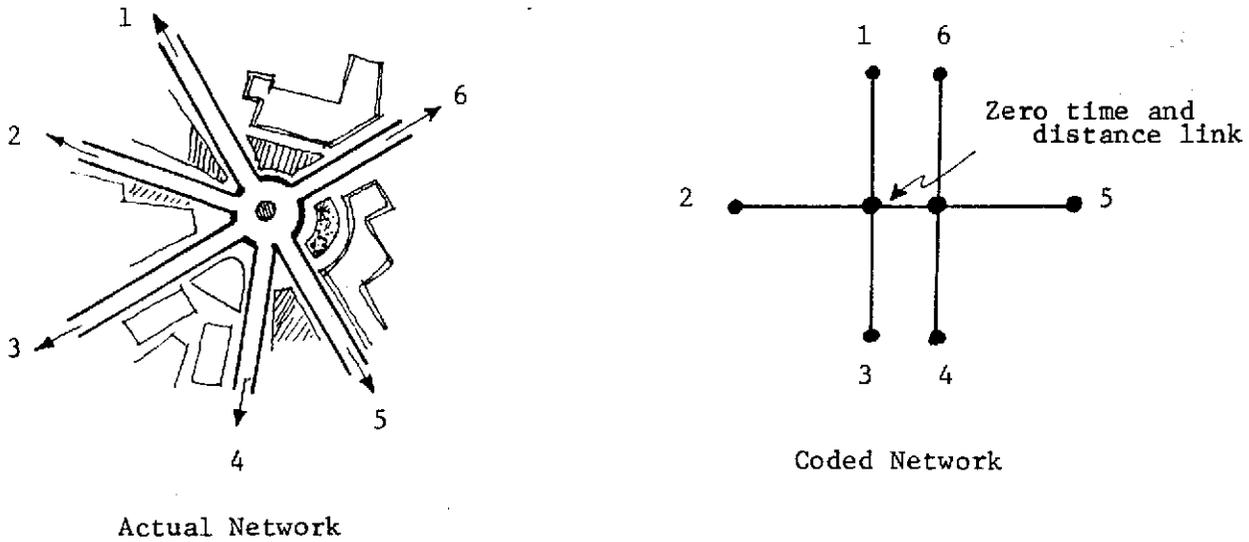
FIGURE 29. ARTIFICIAL LINKS IN THE NETWORK
            (from Bureau of Public Roads,
            June, 1970)

All the nodes of the network are associated with a number, and the general procedure for numbering the nodes is as follows:

from node 1 to n_1 ————————> Centroids of zones where n_1 equal total number of transportation zones.

from node n_2 to n_3 ————————> External stations, jurisdictional boundaries, etc., where $n_2 > n_1 + 1$

from node n_4 to n_5 ————————> Nodes on the traffic network interceptions where $n_4 > n_3 + 1$

The reason for $n_2 > n_1 + 1$ and $n_5 > n_4 + 1$ is to allow for some slack between the different categories of nodes in case of additions and/or modifications.

In some cases the links connecting a node may be assigned a unique number (0-3). These numbers are called the leg numbers. Leg numbers are not an essential item, but must be included at nodes (intersections) where turning movements are to be penalized (delayed) or prohibited. Figure 30 shows a typical coded network. Once the physical transportation network has been coded in terms of nodes linked together, more information about each individual link is necessary, such as:

1. Link distance
2. Link speed or travel time
3. Existing traffic volume
4. Practical capacities

11.1.1 Link Distances

Link distances are obtained directly from the scaled maps.

11.1.2 Link Speed or Traveltime Data

One of the major inputs to the traffic assignment process is a value for speed or travel time on each link in the traffic network. These values are used in the computation of the minimum time path routings between traffic zones which are eventually loaded with vehicular movements between these zones. Speed or travel time runs are usually made during both the peak and off-peak hours. The ADT traffic assignments, peak and off-peak speeds, or times may be combined to represent average daily values. One method currently being used assumes that approximately two-thirds of the daily traffic occurs in the off-peak hours and the remaining one-third occurs during the peak hours. The following formula might be used to determine the average value of travel time:[*]

$$\text{ADT travel time} = \frac{2 \text{ (off-peak travel time)} + 1 \text{ (peak travel time)}}{3}$$

In large transportation studies, it is almost impossible to obtain speed

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[*] Bureau of Public Roads. June 1970.

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External Cordon Line
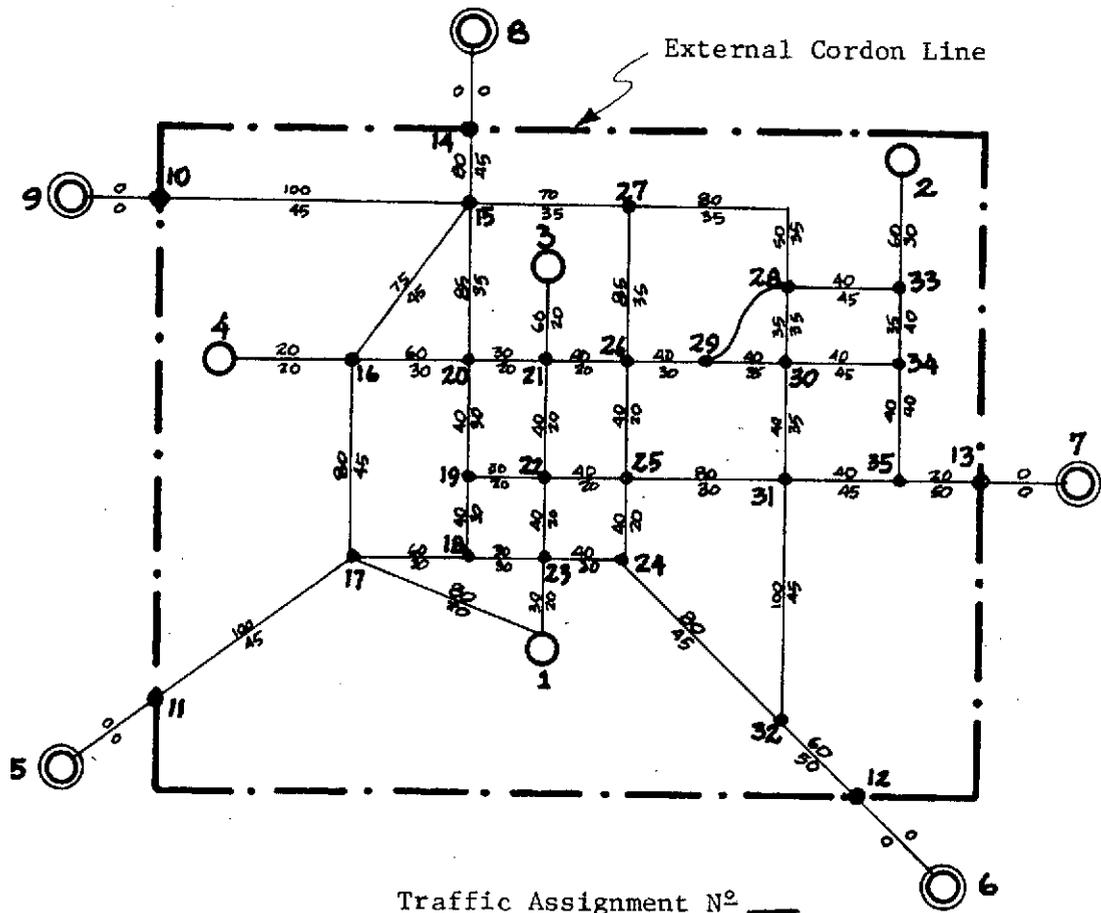
Traffic Assignment N⁰ ____
Urbanopolis, U.S.A.
Scale ____

Legend:

⊚ -- External Stations

○ -- Zone Centroids

●¹⁷ -- Node and Node Number

$\frac{80}{20}$ -- Length of Link in 1/100 miles
Speed on Link (MPH)

Parameters:

4 Internal zones (nodes 1-4)
5 External stations (nodes 5-9)
Last node number = 35

FIGURE 30. CODED NETWORK MAP

counts on every link in the network. In such cases, typical values
of speed or time can be obtained from similar links in the study
or other studies. Speeds and travel times can also be determined
on the basis of the desired highway or street capacity standard.
The desired capacity on a particular facility is dependent upon the
"level of service" to be rendered by that facility. For a more de-
tailed discussion of the level of service concept refer to the 1965
edition of the Highway Capacity Manual. Based on highway or street
capacity and a desired level of service, the speed on a facility
might be determined. Speeds can be obtained for freeways, expressways,
arterials, collectors and locals, which are located in the CBD,
intermediate, suburban and rural area. Table 19 shows the average
speeds, based on design capacity level C.

TABLE 19

AVERAGE RUNNING SPEEDS, LEVEL SERVICE C[*]

Facility Classification	Location			
	CBD (MPH)	Intermediate (MPH)	Suburban (MPH)	Rural (MPH)
Freeway	40	40	50	55
Expressway	30	30	35	40
Arterial	20	25	30	35
Collector	15	20	25	35
Local	10	15	20	25

[*]from Bureau of Public Roads, June, 1970.

Caution must be used when resorting to these procedures, since the
accuracy of the assignment process is dependent upon these values.

11.1.3 Traffic Volume Data

The total traffic volume across selected links are obtained from the traffic survey (cutline counts). Although this information is not considered an integral part of the network description, it does permit the evaluation of the results of an initial traffic assignment.

11.1.4 Street Capacity Data

The practical capacity of each link in the network is calculated from data obtained from the inventory and survey of the transportation facilities. Some of the information needed is curb-to-curb width, parking regulations, type of control devices including signal time, composition of traffic and percentage of turning movements.

11.2 Trip Volume Matrix of the Interzonal Traffic Movement

The O-D survey produces "trip tables" which measure the trips people make independently of the routes that they select, i.e., O-D movement can be represented by some form of desire lines showing the magnitude of the trips on the shortest airline distance between terminal points of the trips. The problem facing the highway planner then is the routing of these trips over the existing and/or proposed facilities. The routing problem created the need for the development of traffic assignment techniques.

11.3 Purpose of Traffic Assignment*

11.3.1 Calibration of Base Year Network

By assigning a trip table to the base year network, imbalances between ground counts and the network can be corrected. Relative network impedances can be adjusted to conform to existing traffic conditions.

_____

*Federal Highway Administration, September, 1972.

11.3.2 Determination of Deficiencies in the Network

By assigning future trip tables (see Trip Generation section), representing future zonal interchanges on the existing network, potential congestion areas become apparent.

11.3.3 Develop and Evaluate Future Systems

By adding new facilities to the existing network, it is possible to simulate future traffic conditions, and make a selection of the most efficient network configuration which will help in the decision making process.

11.3.4 Development of Construction Priorities

After a future network has been developed, a construction schedule for completing that network can be worked out. Several future trip tables can be developed by interpolating between present trip tables and the design year trip tables. These tables then can be assigned to the existing plus the gradually expanding network. Analysis of the congestion conditions will lead to a better construction priority schedule.

11.3.5 Test Alternative Proposals

As changes in transportation policy take place over time, alternatives to the proposed system can be tested using traffic assignment.

11.4 The Moore Algorithm

In all traffic assignment techniques developed to date, it is assumed that the vehicle operator desires to use the route of least impedance when going from one centroid to another. The route of least impedance can be found either manually or by aid of computer. Procedures to find the route of least impedance manually will be omitted since for all practical purposes this technique has been replaced completely by computer procedures.

The most significant development in the field of traffic

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assignment, and the one that made possible the use of computer pro-
cedures, came in 1957 with the presentation of two research papers.
One was by E. F. Moore entitled "The Shortest Path Through a Maze"
and the other by G. B. Dantzig entitled "The Shortest Path Problem."
Before describing the technique known as the "Moore Algorithm,"
it is necessary to define the two possible types of shortest paths
between two points. All routes from one centroid to all others are
referred to as a "tree" or a "vine."

A tree is defined as a record showing the shortest routes
and time of travel from a given zone (centroid) to all nodes in the
highway network.

The vine is described as a tree with additional provisions
that a node may be traversed more than once. This permits realistic
paths where turn penalties and/or prohibitors are involved.

A vine is more accurate than a tree but requires two or three
times as much computer time to determine. To illustrate how the
minimum path (Moore) algorithm works, consider the network shown in
Figure 31. We want to find the shortest path from centroid 1 to
all other centroids, i.e., 2 through 9.

Start at Centroid 1 and proceed along each link emanating
from Centroid 1 upon reaching an intersection (node) one writes the
time it took to traverse the link, plus an arrow pointing backward
along the path just used. Then from each intersection reached, one
starts again and writes down at the next intersection the "cumulative
time," i.e., the previous node time plus the connecting link time.
Special attention has to be paid to the fact that there might be
several alternative links that can reach a particular node. In
this case the link that gives the lowest total cumulative time will
be selected. For example, in this illustration node 18 can be reached
from node 1 either through node 17 or node 23. The cumulative travel
time for each case is as follows:

Alternative Route from Node 1 to Node 18

Path	Cumulative Time
1-17-18	5
1-23-18	4

The shortest route between nodes 1 and 18 is through links 1-23 and 23-18 with a travel time equal to 4, and an arrow will be placed on node 18 pointing in the direction of link 23-18. Following the same procedure one gets a network as shown in Figure 31.
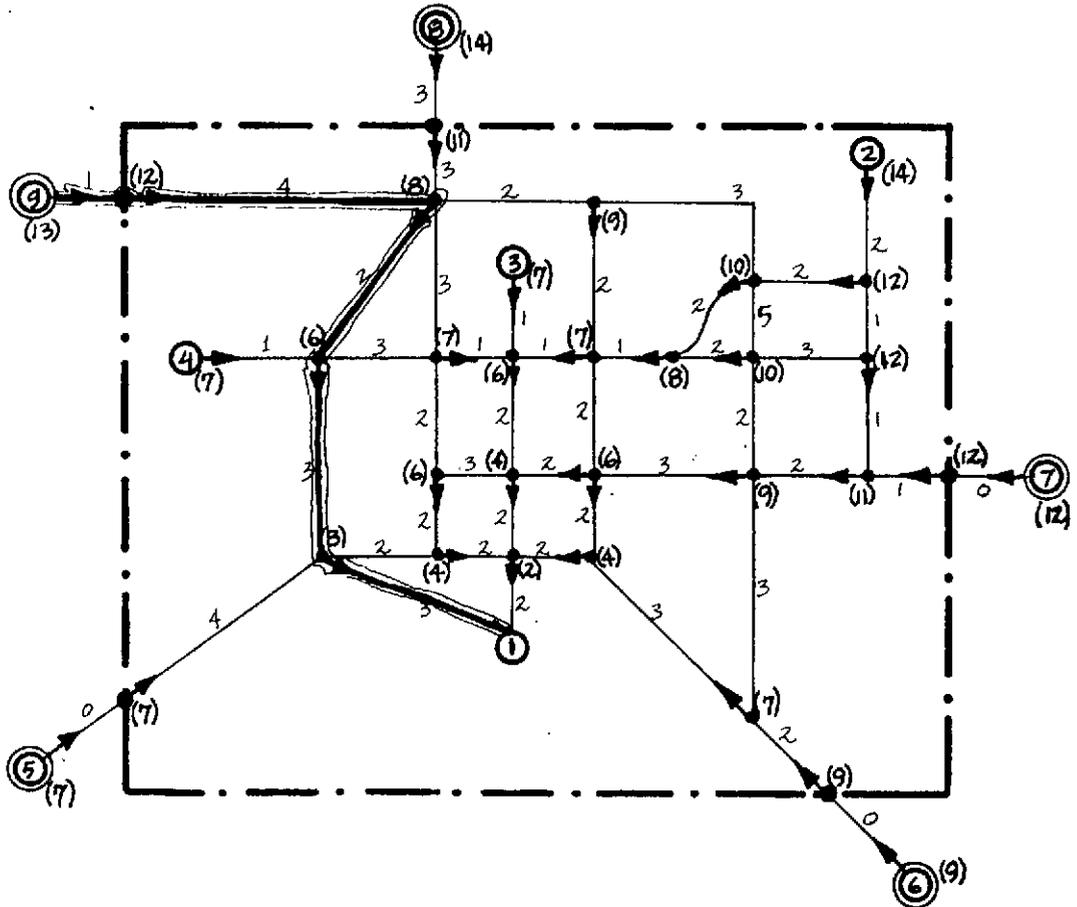

FIGURE 31. LINK TRAVELTIMES IN A NETWORK

To find the shortest route from node 1 to node 9 in the network
one starts at node 9 and follows the arrows until reaching node 1.
The minimum travel time between nodes 1 and 9 is equal to 13 min-
utes. Figure 31 shows this minimum path. The procedure illustrated
above is just one of the many variations of the Moore Algorithm.
When using a computer a more mathematical procedure has to be used.
Figure 32 shows the final minimum path tree trace from Centoid 1.
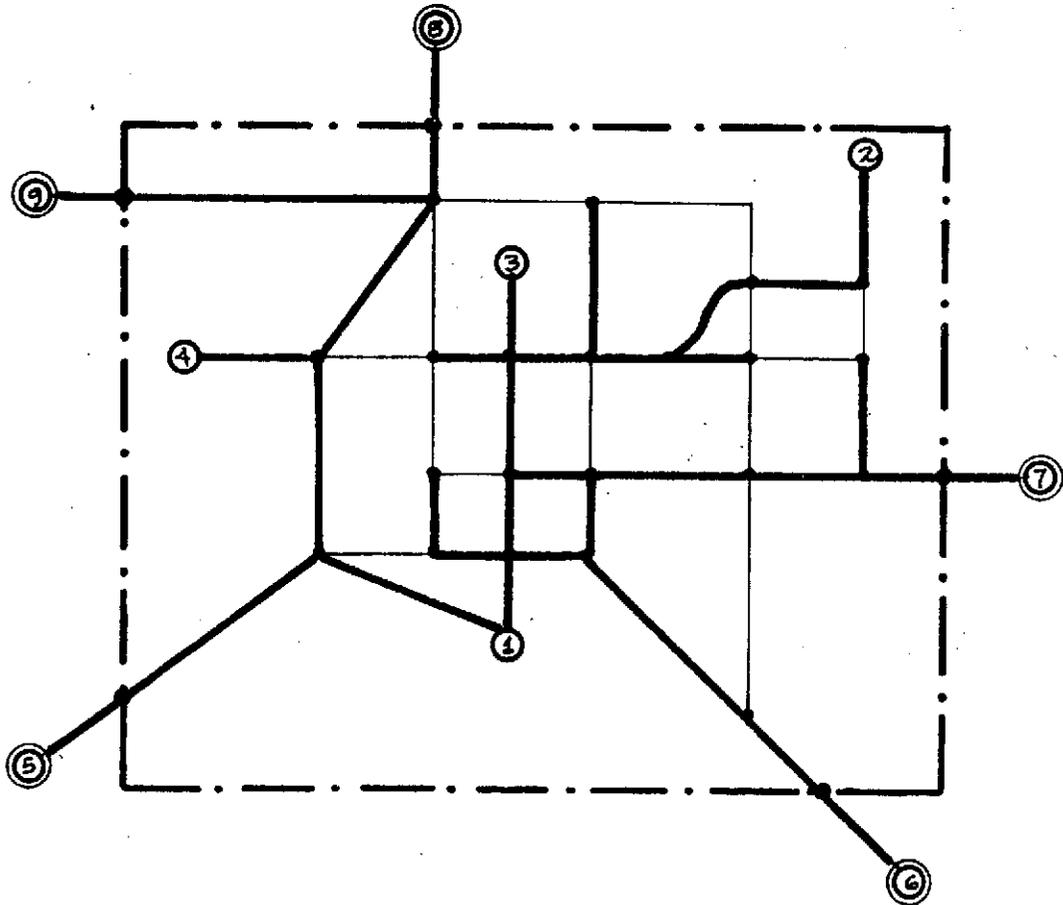
FIGURE 32. MINIMUM PATH TREE IN A NETWORK

The following is a general mathematical formulation of the
minimum path algorithm. Assume that a maze of interconnected nodes
(Figure 33a) is represented by a set of nodes p_i that belong to a

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set U where i = 1, 2, 3, . . . , u. Any network such as in Figure 33a that has an origin node (p_0) can be represented by a hierarchial tree structure as shown in Figure 33b by rearranging the positions of the nodes and keeping their interconnection with other nodes unchanged.

Node classification according to different hierarchial levels depends on the minimum number of connections between origin node p_0 and the node in question. For example node p_4 in Figure 33a has several possible paths to node p_0, they are:

$$P_0 - P_4,$$

$$P_0 - P_1 - P_4,$$

$$P_0 - P_2 - P_4,$$

$$P_0 - P_3 - P_5 - P_4, \text{ etc.}$$

but the path of minimum interconnections between p_0 and p_4 is equal to 1, so node p_4 belongs to level 1.

We can define hierarchial levels 0, 1, 2, . . . , n in terms of sets as follows:

$$S_0 = \text{set of all nodes up to level 0},$$

$$S_1 = \text{set of all nodes up to level 1},$$

.

.

.

$$S_n = \text{set of all nodes up to level } n.$$

Let us also define new sets as follows:

$$Q_0 = S_0$$

$$Q_1 = S_0^{\,c} \cap S_1$$

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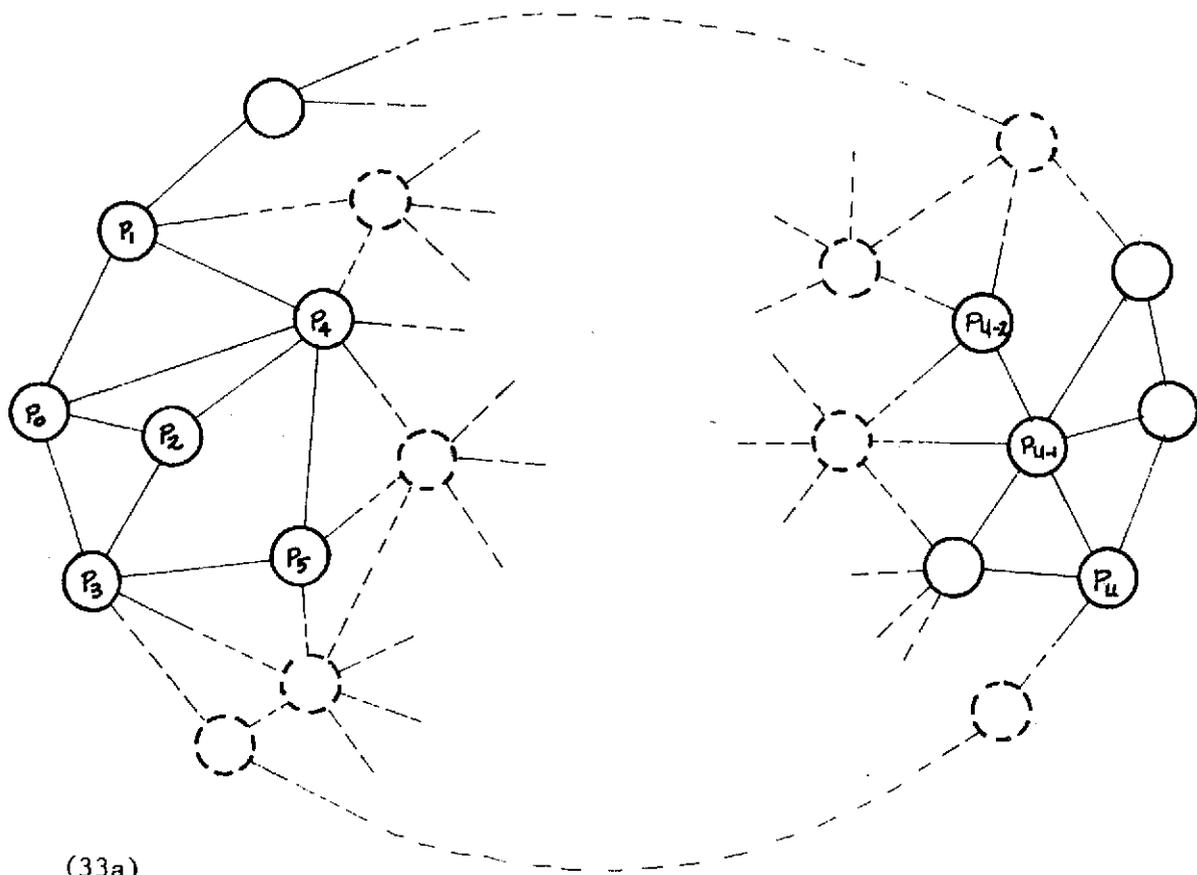
(33a)
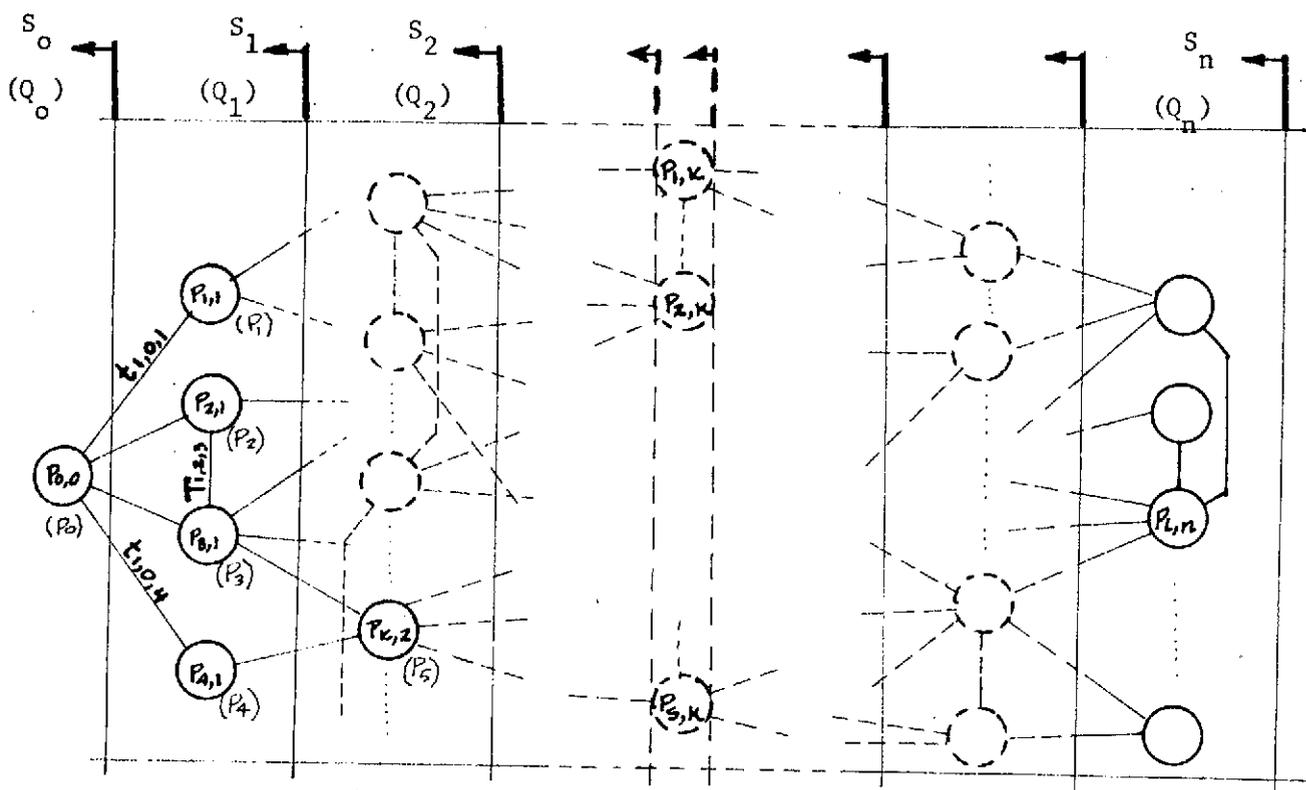
(33b)

FIGURE 33.   A TYPICAL INTERCONNECTED NETWORK

$$Q_2 = S_1^c \cap S_2$$

.

.

.

$$Q_n = S_{n-1}^c \cap S_n$$

where

$$S_n^c = \text{complement of set } S_n$$

Q_n is the set of nodes belonging to set S_n but not to set S_{n-1}, i.e., the set of all nodes having a minimum number of connections with node p_o and equal to n, where n is the number of connections.

Re-define the set of nodes in Figure 33b in the following way:

$$P_{i,j} = \text{node } i \text{ in set } Q_j$$

Nodes p_1, p_2, p_3, p_4 in Figure 33a are re-defined as $(p_{1,1})$, $(p_{2,1})$, $(p_{3,1})$ and $(p_{4,1})$ respectively in Figure 33b.

Assume that the shortest route through the network has been found from the origin to all nodes in set Q_k. The set of shortest routes can be defined as follows:

$$M_k = (m_{1,k}, \ m_{2,k}, \ \cdots \ m_{i,k}, \ \cdots \ m_{\ell,k})$$

where

$$M_{i,k} = \text{shortest route from } P_{o,o} \text{ to } P_{i,k}.$$

$$\ell = \text{total number of nodes in } Q_k.$$

Then the minimum route from the origin node $p_{o,o}$ to the set of nodes belonging to Q_{k+1} will be given by

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$$M_{k+1} = M_k + \min (t_{k+1,i,j} + T_{k+1,u,v})$$

where

$t_{k+1,i,j}$ = travel time from any node $p_{i,k}$ in Q_k to any

node $p_{j,k+1}$ in Q_{k+1}

$T_{k+1,u,v}$ = travel time from any node $p_{u,k+1}$ and

$p_{v,k+1}$ belonging to set Q_{k+1}

The minimum route from $p_{o,o}$ to the set of nodes belonging to Q_k

is given by

$$O_k = \min M_k$$

11.5 Traffic Assignment Techniques

Traffic assignment, in simple terms, is the process of de-
termining the amount of usage of segments of a traffic network. The
process is accomplished by first determining the most reasonable
route through a network between two points. Once the path has been
determined, the number of trips that desire to travel from the
origin point to the destination point are routed along the path
and the different links usages are accumulated. The process is
completed for all points in the network where trips originate or
terminate. In effect traffic assignment is a simulation of link
volumes in a highway network.

There are several techniques for doing traffic assignment:

- Free Assignment
- Capacity Restraint Assignment
- Diversion Assignment

11.5.1 Free Assignment

Also referred to as the all-or-nothing technique, this

technique loads all the trips between pairs of nodes onto one path
which represents the optimum route for the trip impedance selected.
Since certain facilities in the network are included in the paths
of many zonal pairs and there is no upper (or lower) limit to how
much traffic any particular facility will be assigned, the result
quite often is extreme over (or under) assignment. This type of
assignment reflects the route drivers would prefer to take if con-
gestion were not a factor. The free assignment is a comparatively
quick and simple procedure and therefore is the least expensive in
terms of computer costs. For areas under 150,000 population this
type of assignment is usually all that is needed for base year net-
work calibration and traffic forecasts.

11.5.2 Diversion Assignment

The weakness of the free assignment is the unrealistic
loadings that result from a one-path route between zone pairs. An
alternate method is to allow several routings between the considered
points of origin and destination. This method assumes that a trip
is distributed by some criteria so that different alternative routes
will be chosen.

In this method a relationship is developed (diversion curve)
between some parameter associated with travel (time, money,safety)
and traffic volume. This relationship is determined by interview,
traffic counting, etc. The possible routes between zones are then
examined to determine the percentage of trips each route will be
assigned, based on the relative attractiveness of each route.

The general form of diversion curves currently utilized is
shown in Figure 34. Basically the curve implies that when the ratio
of a new facility time to an old facility time is low, then a high
proportion of existing traffic will be diverted to the new facility.
When the ratio is high, only a small proportion will be diverted.
Whether the curve starts at exactly 100% diverted and goes down to
0% is not important, though some people will tend to never use the

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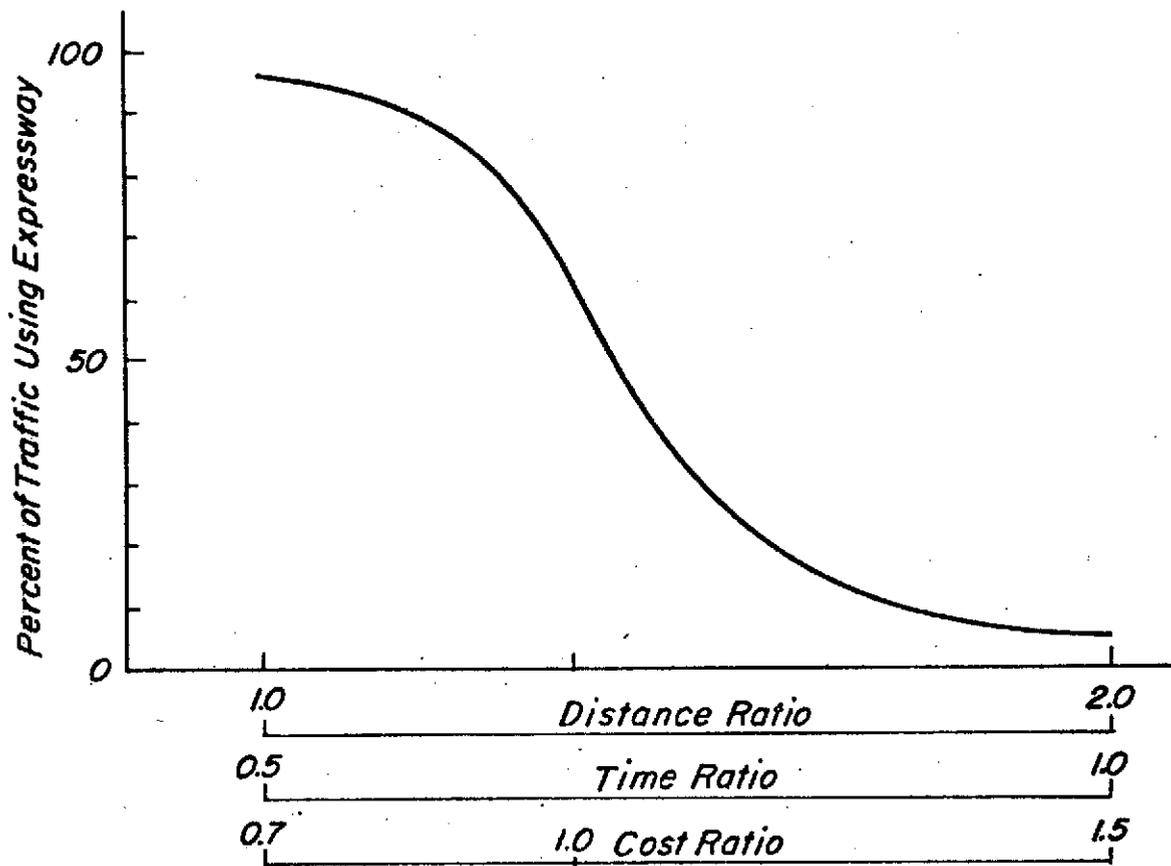
FIGURE 34. A GENERAL DIVERSION CURVE

(from: Ridley, T. M., Feb., 1968. p. 19.

facility and some always use it.

An additional complication arises from the fact that no
journey is made wholly by freeway. For this reason the time ratio
should be measured from point of choice to point of choice rather
than from the whole journey. This subject will be elaborated on in
the discussion that follows.

There are three types of diversion curves in current use:
(1) time ratio curve (BPR); (2) distance and speed ratio curve
(Detroit Study); and (3) time and distance differential curve
(California).

The Bureau of Public Roads time-ratio curve (Figure 35) bases the percentage of trips to be assigned to a freeway facility on the ratio of the travel time via the freeway to the travel time via the quickest alternate route. The percentage of trips using the freeway varies as an S-shaped curve for 100 per cent at a time ratio of 0.5 or less to zero per cent at a time ratio of 1.5 or more. If the travel time via the freeway is equal to the travel time via the alternate route (time ratio equal to 1.0), approximately 42 per cent of the trips are assigned to the freeway because the freeway trips are at a faster speed even though the travel distance is generally longer.

The speed ratio curves developed for the Detroit Area Transportation Study (Ridley, 1968) consist of a family of curves relating the percentage of freeway use to speed and distance ratios. These curves are also S-shaped for normal conditions. With a speed ratio 1.0 and a distance ratio of 1.0 approximately 45 per cent of the trips are assigned to the freeway. Since these curves represent a three-dimensional surface with an undefined mathematical relationship, they are difficult to use in a computer application (Figure 36).

The California time and distance curves consists of a family of hyperbolas (Figure 37). With equal time and distance on the freeway and on the best alternative, 50 per cent of the trips are assigned to the freeway. These curves are expressed by the equation

$$P = 50 + \frac{50 \left(d + \frac{1}{2} t\right)}{\left(d - \frac{1}{2} t\right)^2 + 4.5}$$

where

P = percentage of freeway usage,

d = distance saved in miles via the freeway, and

t = time saved in minutes via the freeway.

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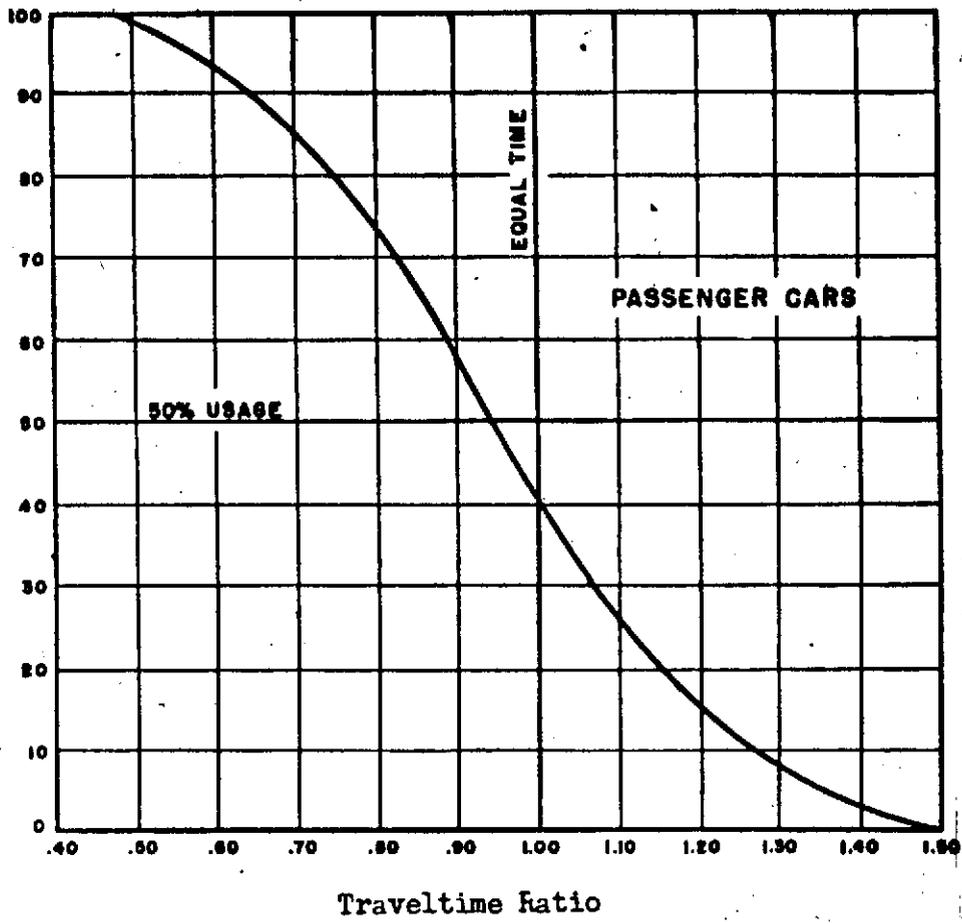
FIGURE 35.   TIME RATIO DIVERSION CURVE

(from: Bureau of Public Roads. 1964.   p. 12)
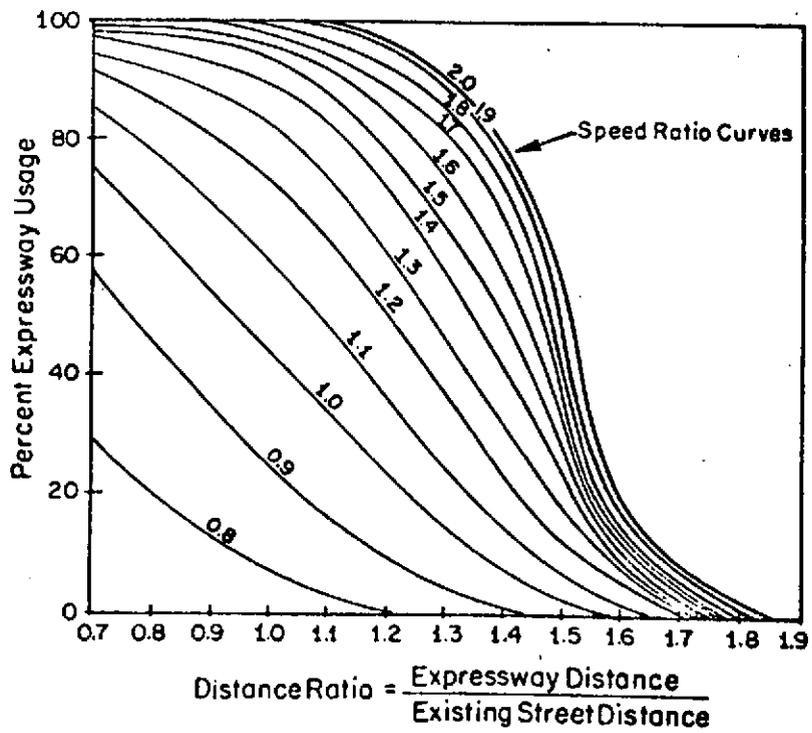
FIGURE 36. DETROIT STUDY DIVERSION CURVE
(from: Ridley, T. M., Feb., 1968)
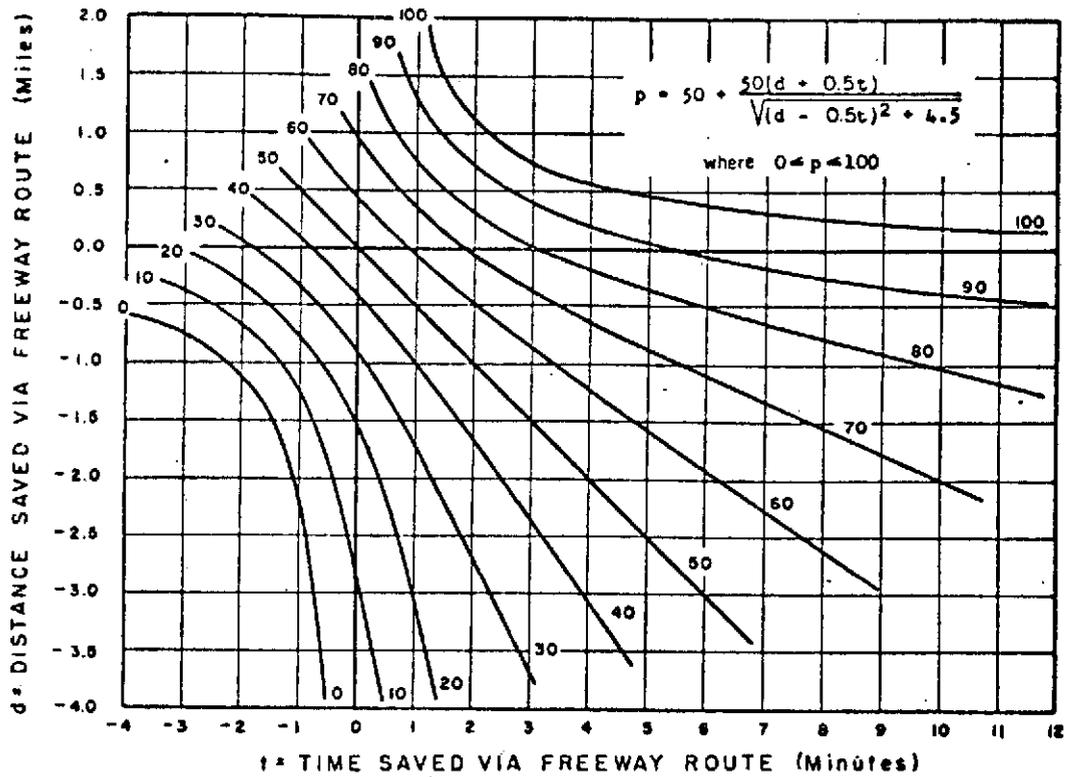
FIGURE 37.   CALIFORNIA STUDY DIVERSION CURVE

(from: Ridley, T. M., Feb., 1958)

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The Bureau of Public Roads (1964) diversion curve, which will be referred to in a subsequent discussion was developed to be applied only at "points of choice."

A point of choice is defined as that point where the arterial and freeway routings diverge from a common path at the origin end of the route or the last point where the freeway and arterial routes converge to a common path at the destination end of a route. Points 2 and 5 in Figure 38 are considered points of choice since links 1-2 and 5-6 are common to both the freeway and the arterial route when traveling from 1 to 6 or visa versa.

Diversion curves have been developed for application at points of choice to allow reasonable diversion to freeways when only short sections of a freeway are used in long routings. Otherwise time ratios close to 1.0 would nearly always be obtained.

Diversion assignment requires that there be two routings for each interzonal movement (arterial street system and freeway system). This allows either a time ratio, a speed ratio, or a time and distance ratio, to be computed between the two routings for the interzonal movement.

The Moore Algorithm is used to compute the minimum paths (trees) for each network system independently. Also, in the calculation of the trees the traffic must be forced to use the freeway facilities for a part of each zone-to-zone movement if it is likely that any part of a movement might divert to the freeway facilities even though the routing may be longer in total time than the routing over the arterial street system. If this were not the case, no time ratios greater than 1.00 would occur.

The technique of forcing the use of a proposed facility is accomplished by reducing the travel time on the freeway links during the calculation of the arterial plus freeway system trees.

To further clarify the time reduction feature, refer to Figures 35 and 39a.

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proposed freeway route
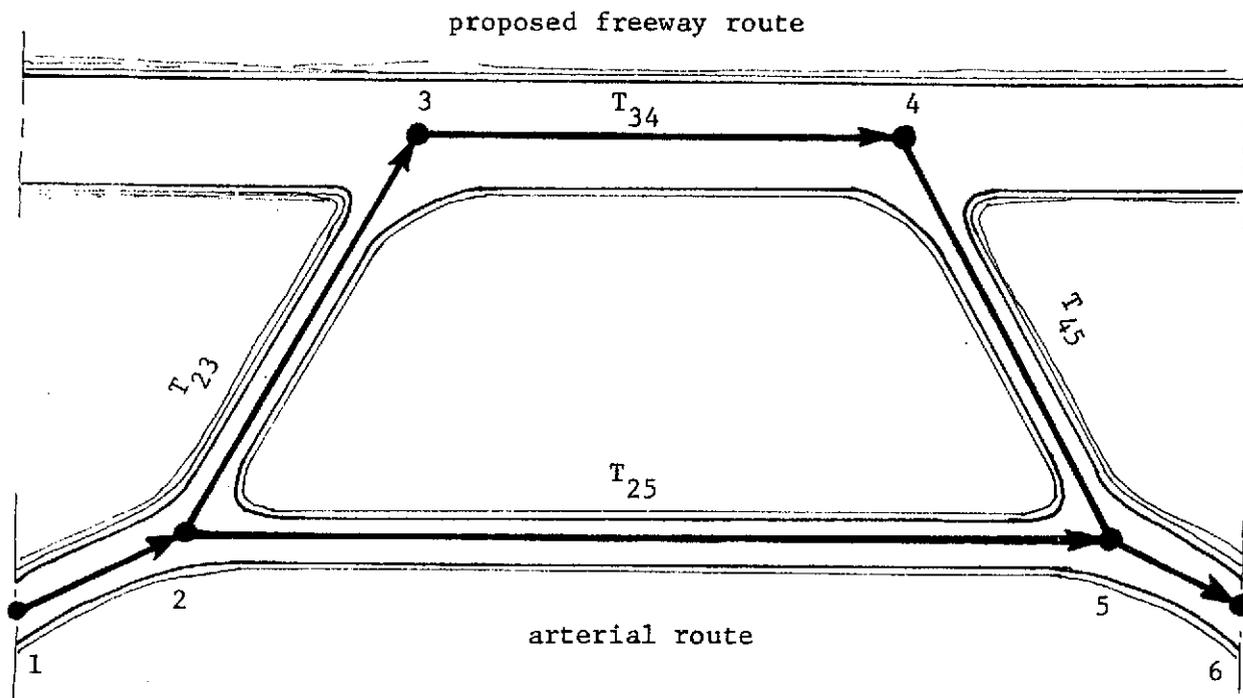
1, 6 -- terminals (centroids) of an interzonal traffic movement

2, 5 -- points of choice

T_{12} -- traveltime of Link 1-2

T_{23} -- traveltime of Link 2-3

T_{25} -- traveltime of Link 2-5

T_{34} -- traveltime of Link 3-4

T_{45} -- traveltime of Link 4-5

T_{56} -- traveltime of Link 5-6

FIGURE 38.   SCHEMATIC DIVERSION TO A FREEWAY

(from: Bureau of Public Roads.   June, 1964.   p. V-15)

If $1 - 2 - 3 - 4 - 5 - 6$ is the minimum path (Figure 38) then

$$T_{23} + T_{34} + T_{45} < T_{25}$$

and if

$$\frac{T_{23} + T_{34} + T_{45}}{T_{25}} \leq 1.5$$

then the percentage diversion to the freeway can be found from the diversion curve (Figure 35).

On the other hand if

$$\frac{T_{23} + T_{34} + T_{45}}{T_{25}} > 1.5$$

then the time ratio is beyond the limits of diversion curve and this would result in zero assignment to the freeway.

It is helpful to develop a relationship of

$$\frac{T_{23} + T_{45}}{T_{25}} \quad \text{(ratio of access route travel time and arterial travel time)}$$

and

$$\frac{T_{34}}{T_{25}} \quad \text{(ratio of freeway segment travel time and arterial travel time)}$$

for $1.0 \leq T.R. \leq 1.5$ where

T.R. = travel time.

If $T_{23} = T_{45} = 0$ (1-11)

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then travel time ratio $= \dfrac{T_{23} + T_{34} + T_{45}}{T_{25}} = \dfrac{T_{34}}{T_{25}}$, $\qquad$ (2-11)

and max $\dfrac{T_{34}}{T_{25}} = 1.5$ (i.e., trips can be diverted to the freeway according to diversion curve).

Also notice that $\dfrac{T_{23} + T_{45}}{T_{25}} = 0$.

This defines point "a" in Figure 39a.

If $\qquad T_{23} + T_{45} = T_{25}$

then the time ratio $= \dfrac{T_{23} + T_{34} + T_{45}}{T_{25}} = \dfrac{T_{34} + T_{25}}{T_{25}}$, $\qquad$ (3-11)

$$= \dfrac{T_{34}}{T_{25}} + 1. \qquad (4\text{-}11)$$

But since $\dfrac{T_{23} + T_{34} + T_{45}}{T_{25}} \leq 1.5$ if diversion can occur, then

$$\dfrac{T_{34}}{T_{25}} + 1 \leq 1.5 \longrightarrow \dfrac{T_{34}}{T_{25}} \leq 0.5,$$

and

$$\dfrac{T_{23} + T_{45}}{T_{25}} = 1 \quad \text{from (3-11)}$$

This defines point "b" in Figure 39b.

The line joining points a and b define the boundary between no assignments (time ratio >1.5) to the freeway above the line and assignment to the freeway below the line.

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For $0 \le \text{T.R.} \le 1.0$,   (5-11)

if $T_{23} = T_{45} = 0$,   (6-11)

then $T_{34} < T_{25}$ from (2-11) and (4-11) and the minimum path from nodes 1 to 6 is $1 - 2 - 3 - 4 - 5 - 6$,

and travel time ratio $= \dfrac{T_{34}}{T_{25}}$.

also max $\dfrac{T_{34}}{T_{25}} = 1$ and $\dfrac{T_{23} + T_{45}}{T_{25}} = 0$

This defines point c in Figure 39a.

If $T_{23} + T_{45} \ge T_{25}$ (7-11)

Then path $1 - 2 - 3 - 4 - 5 - 6$ is not a minimum path.

We know that

$$\frac{T_{23} + T_{34} + T_{45}}{T_{25}} \le 1 \text{ from (5-11)}$$

so $T_{34} = 0$ from (5-11) and (6-11)

and $\dfrac{T_{23} + T_{45}}{T_{25}} = 1 \text{ with } \dfrac{T_{34}}{T_{25}} = 0.$

This relationship defines point d in Figure 39a.

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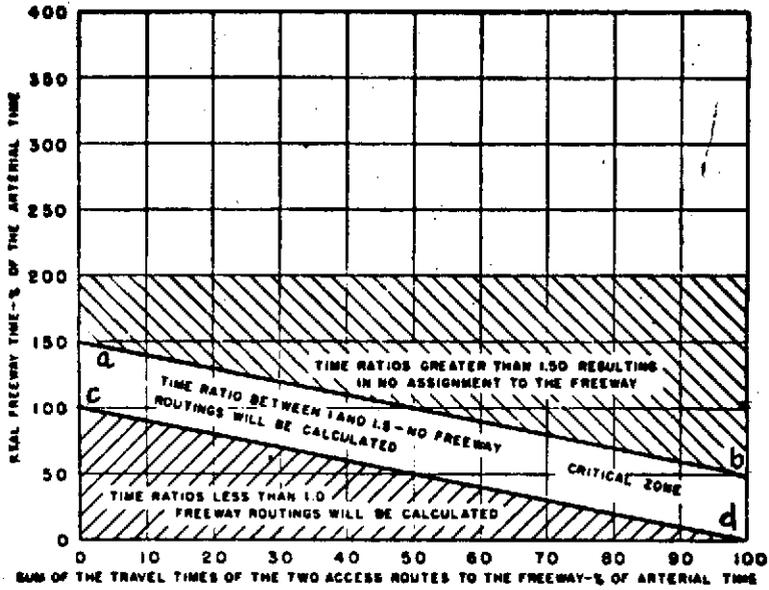
(39a)   Calculation at Fulltime
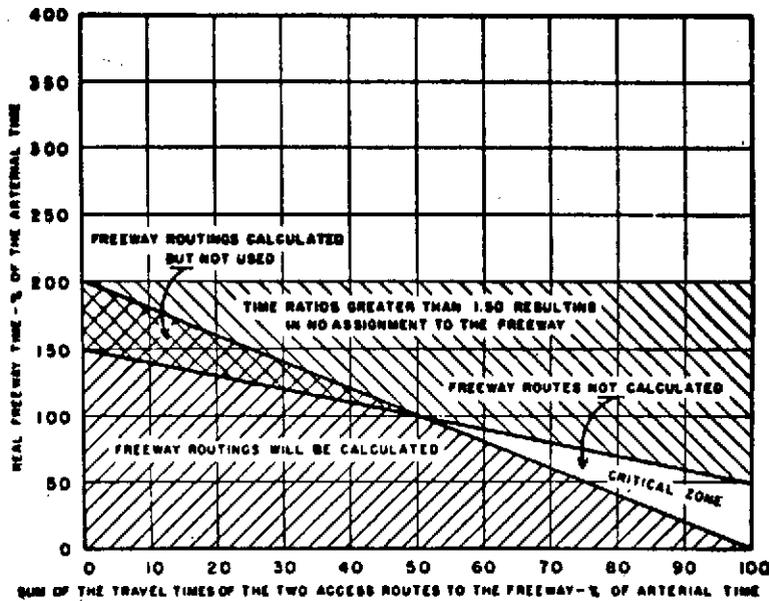

(39b)   Calculation at Half-Time

FIGURE 39.   FREEWAY ROUTE CALCULATIONS

(from: Bureau of Public Roads, 1964)

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Figure 39b shows the situation that would result if the freeway travel times were halved during the free calculations and then restored to their full values before time ratios are calculated. The unshaded area shows the critical area where time ratios would be between 1.0 and 1.5 but no routings involving a portion of the freeway route would be calculated. Note that the critical area has been reduced to one-quarter of the critical area shown on Figure 39a.

Freeway link travel time could be reduced even further, but experience has shown that the diversions become somewhat unrealistic when the travel times are reduced by more than one-half.

Figure 40 shows a plot of critical area versus the fraction of the original time to which the time is reduced. Cutting the freeway travel time to zero would force all routings to use a portion of the freeway system, but the criteria for route selection would be lost.

To summarize, the problem of forcing traffic to use the freeway or proposed routes when the travel time is adverse to the arterial street system route (time ratios between 1.0 and 1.5) is a difficult one when using some other method for route selection. However, reducing the travel time on the freeway links allows the same free assignment program to be used for both the arterial street network and the arterial plus freeway network.

11.5.3 Capacity Restraint Assignment

Capacity restraint is a method by which assigned link volumes are compared to link capacities and through an iterative process travel times on the links are adjusted to reflect more realistic operating conditions on the network. The ratio of assigned volume to capacity is referred to as the "Volume-Capacity ratio" or simply as "V/C." Traffic can be assigned more realistically to a network if the practical capacities of the links (or as many links as possible) are considered (Figure 41).

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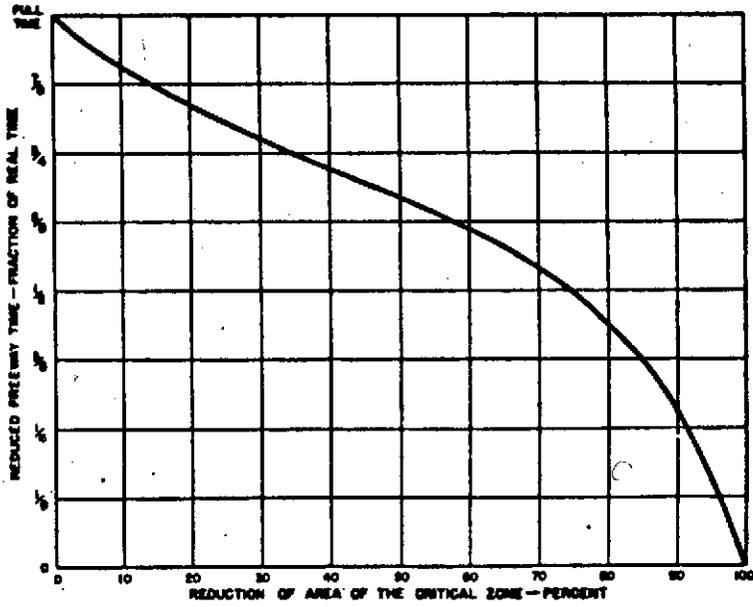
FIGURE 40. RELATION OF THE CRITICAL ZONE AREA TO THE
FREEWAY TIME REDUCTION

(from: Bureau of Public Roads, 1964)
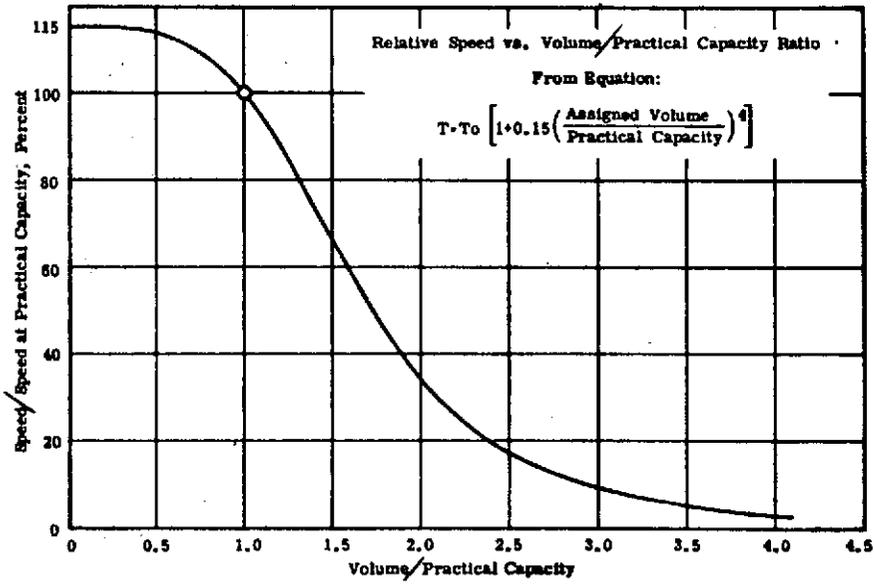
FIGURE 41. CAPACITY RESTRAINT RELATIONSHIPS

(from: Bureau of Public Roads, 1970)

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As the user prepares the network for computer simulation, the practical capacity and the speed at which traffic will flow on each link in the network is fed into the computer. The paths of origin and destination are calculated and traffic assigned to the proper links. The resultant "loaded network" is then examined automatically on a link by link basis to determine the V/C ratio. The adjusted link speed and/or its associated travel impedance is computed by use of the following equation

$$T = T_o \quad 1 + 0.15 \ (V/C)^4$$

where

V/C = assigned volume/practical capacity

T = balance travel time at which V can travel on the subject link

T_o = free flow travel time (balance travel time at practical capacity x 0.87 travel time at zero volume)

Figure 41 shows graphically this relationship.

Direct use of the balance travel impedance for a successive traffic assignment tends to result in an extreme oscillation in the link volumes. To offset this, a different link travel impedance is obtained by combining the balance travel time with the assignment travel time. The combination is usually weighted so that the new impedance is one-fourth the difference between the base time and the balance time, or expressed mathematically,

$$T_a = 0.75 \ T_{base} + 0.25 \ T$$

where T_a = assignment link travel impedance for use in the next assignment. The following is an illustration of the capacity restraint method.

Suppose that after the tree building process was completed and the network load, the distribution shown in Figure 42 was obtained.

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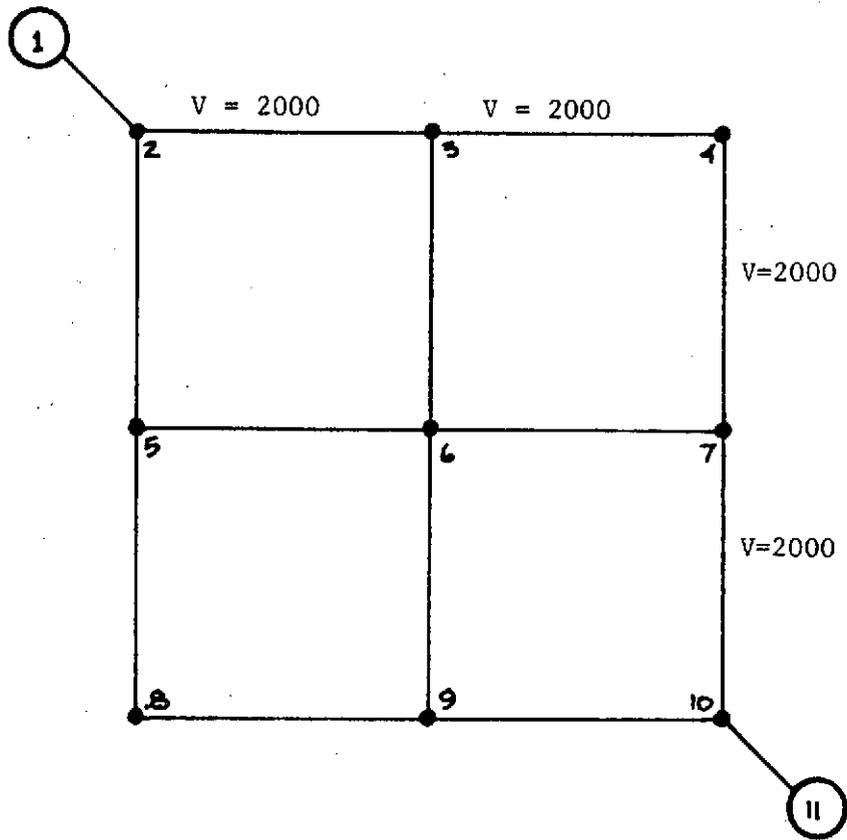
FIGURE 42. TRAFFIC DISTRIBUTION IN A NETWORK
BY FREE ASSIGNMENT (interation one)

(from: FHA. Urban Transportation Planning Course Notes.
Sept. 1972. p. 3)

Given

Link 3-4,

Volume = 2000,

Capacity = 1000,

T_o = observed travel time = 3 minutes,

T_1 = base time or last assignment time = 3 minutes,

T_2 = new computed travel time,

T_3 = new modified assignment time,

$T_2 = T_o [1 + 0.15 (V/C)^4]$, and

$T_3 + 3 [1 + 0.15 (\frac{2000}{1000})^4] = 10.2$ minutes.

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To reduce the oscillation effect of time change, T_3 is weighted with previous assignment time T_1,

$$T_3 = .75 \, T_1 + .25 \, T_2,$$
$$\quad = .75 \, (3) + .25 \, (10.2), \text{ and}$$

$$T_3 = 4.8 \text{ minutes.}$$

The travel time on link 3-4 has been increased to 4.8 minutes due to congestion. This process is carried out for all links in the network. As a result of the increased travel time on link 3-4, a new minimum path and assignment results (Figure 43a).
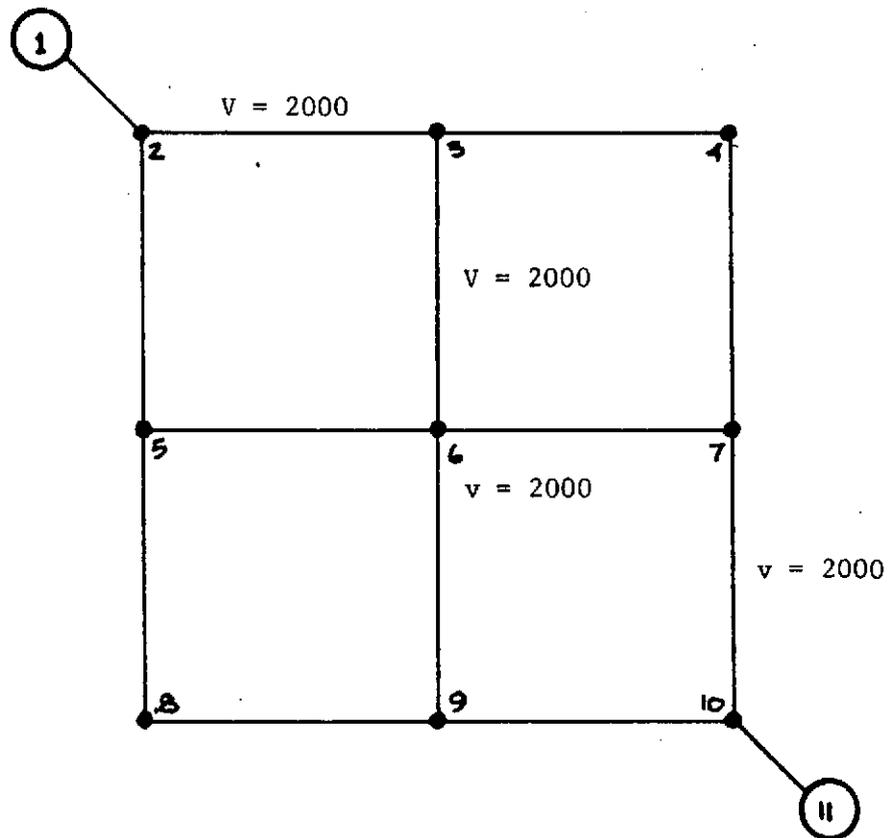
FIGURE 43a.   CAPACITY RESTRAINED TRAFFIC DISTRIBUTION
(iteration two)

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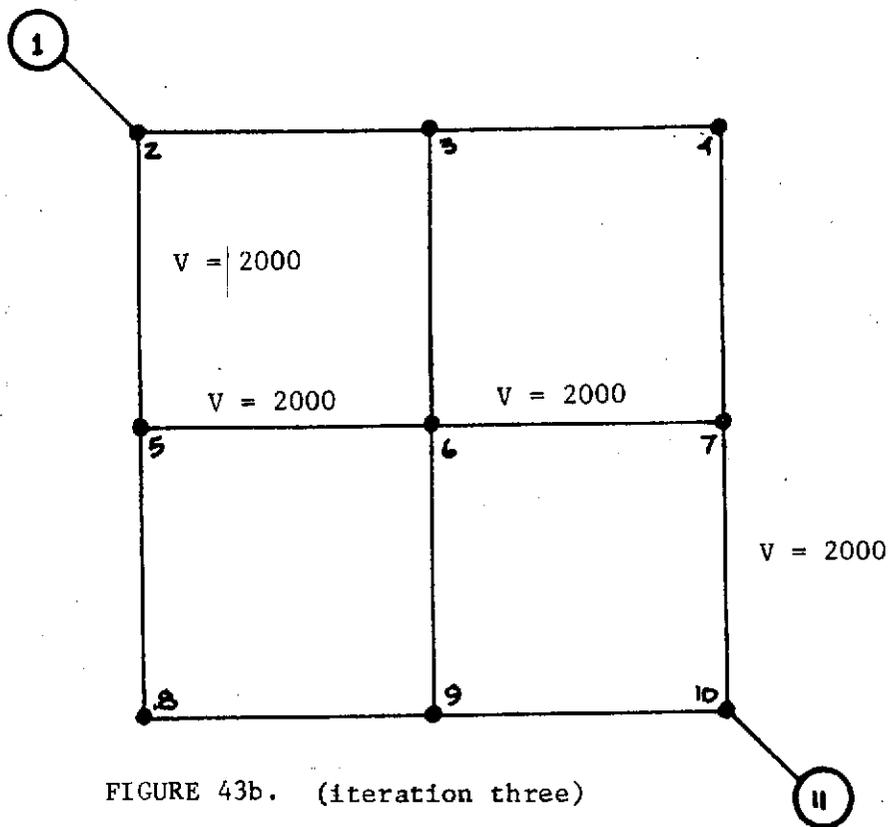
FIGURE 43b.   (iteration three)
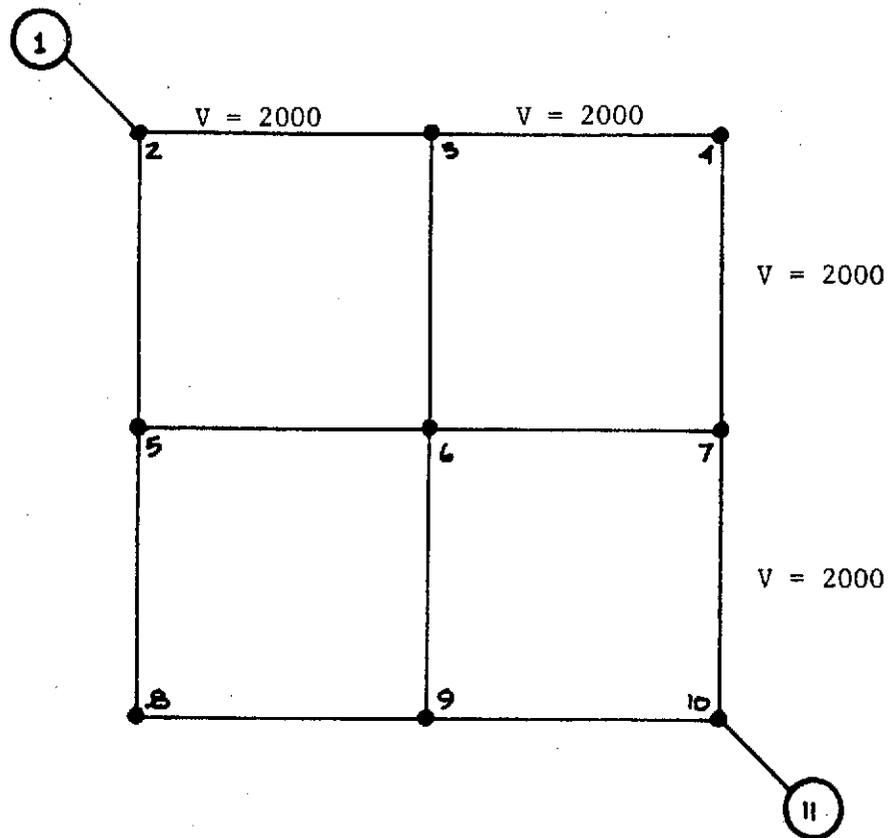
FIGURE 43c.   CAPACITY RESTRAINED TRAFFIC
DISTRIBUTION (iteration four)

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The restraint procedure described above is employed in subsequent iterations. Assume that iterations three and four produce assignments as shown in Figures 43b and 43c.

The results of the four individual assignments are averaged together to produce the final average assignment shown in Figure 44.
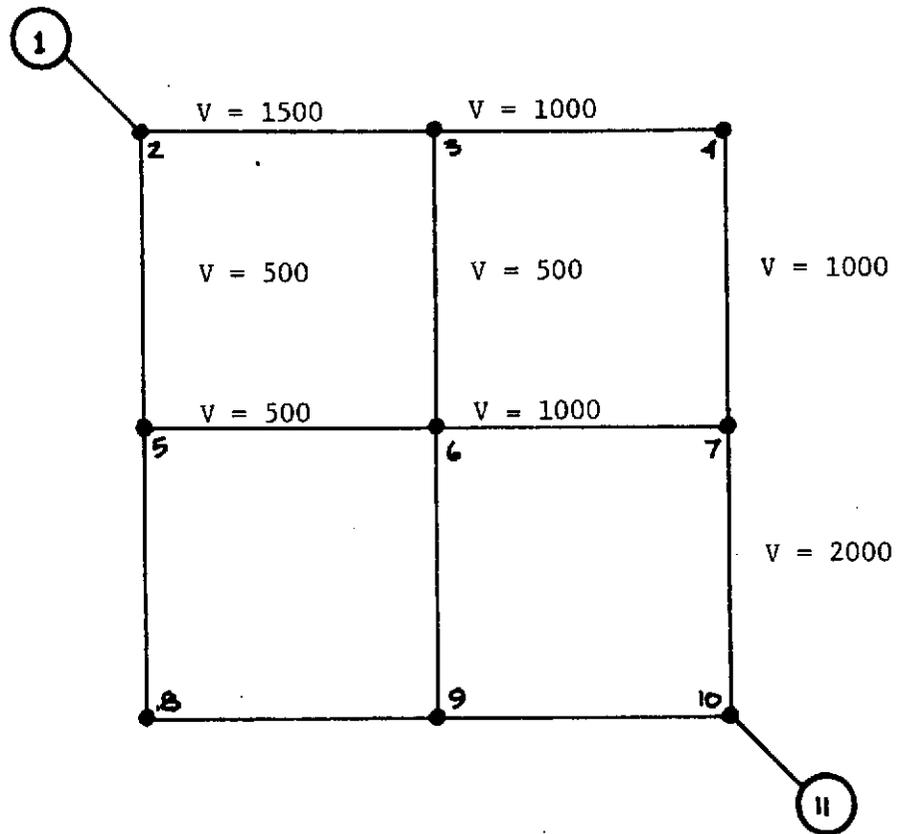
FIGURE 44. FINAL TRAFFIC DISTRIBUTION (AVERAGE
OF THE FOUR INTERATIONS FROM THE
CAPACITY RESTRAINT EXAMPLE)

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CHAPTER XII

FORECASTING FUTURE TRAVEL CONDITIONS

The forecasting of future travel demand is the ultimate
objective of the transportation study. There are three major con-
ditions that must be met before forecasted land use (socio-economic)
data can be utilized to develop future urban area travel patterns:

1. Mathematical expressions relating present trip pro-
   ductions and attractions to land use and socio-economic
   characteristics must be formulated (Chapter IX).

2. A calibrated network which reflects the existing
   physical transportation facilities must be described
   (Chapter XI).

3. A calibrated trip distribution model that accurately
   describes present travel distribution patterns must
   be formulated (Chapter X).

The total trip productions and attractions are based upon
an estimate of future economic activity, land use and population
indicators as mentioned in

relationship between trip productions and attractions and socio-
economic characteristics will remain constant over time. Based on
this assumption, it is possible to forecast future trip productions
and attractions by simply updating and forecasting the future socio-
economic characteristics (independent variables) and substituting
them into the appropriate mathematical equations developed for pre-
sent conditions.

A proposed transportation system is determined for the
future time period. The location and extent of this system is in-
fluenced by present points of congestion and probable changes in
land development patterns. Once the proposed system is coded and

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described in the same manner as the present network (for computer usage), the minimum path traveltimes between all zone pairs for the proposed system can be calculated.

Traveltime factors as developed for the present data are assumed to remain constant over time.

If zone-to-zone adjustment factors (kij) were found necessary for the present time period, they may also be necessary in the future. These factors are applied in the future based on their present relationship to specified socio-economic characteristics.

The distribution model provides the transportation planner with an effective tool to relate the characteristics of land use to the characteristics of the transportation system in order to simulate the distribution of trips. The feedback from the transportation system to the land use and vice versa is the key to the transportation system analysis.

> "The transportation planner has many alternate approaches to systems analysis available to him. Alternate land use configurations can be studied with respect to a single transportation plan, or more likely, alternate transportation systems can be studied with respect to a given land use plan. The number of possible configurations of land use and transportation systems requires a systematic approach to the problem."*

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*Bureau of Public Roads, 1968.

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APPENDIX A

REGRESSION EQUATION BY LEAST SQUARES

In regression analysis we attempt to derive an analytical relationship between two or more groups of matched observations, so that it would be possible to predict the value of one by knowing the value of the other. The variable to be predicted is referred to as the dependent variable, and the value used in predicting it is called the independent variable. In the case of simple regression, only two variables are involved (one dependent and one independent variable). In such a case the data can be represented by points in a two dimensional graph as shown in Figure A-1. Such an array of points is known as a scattergram.

In trying to fit the line of a regression equation to define such a scattergram, we attempt to equalize the sum of the positive deviations from the line with the sum of the negative deviations. This procedure can be simplified by squaring all the deviations so that instead of trying to offset negative against positive deviations, the problem becomes one of minimizing the summation of the deviations squared. A perfect fit occurs when the summation of the deviations squared is equal to zero, i.e., all data points fall on the line defined by the regression equation.

In Figure A-1 the equation of the line is $Y = a + bX$, and our objective is to minimize $\Sigma\ e_i$

By multiplying both sides by -1 and adding Y_i to both sides, we obtain:

$$Y_i - \hat{Y} = Y_i - a - bX, \text{ where } Y_i \text{ is the observed value and}$$

$\hat{Y}$ is estimated value.

$$Y = a + bX$$
(regression equation)

FIGURE A-1: SCATTERGRAM
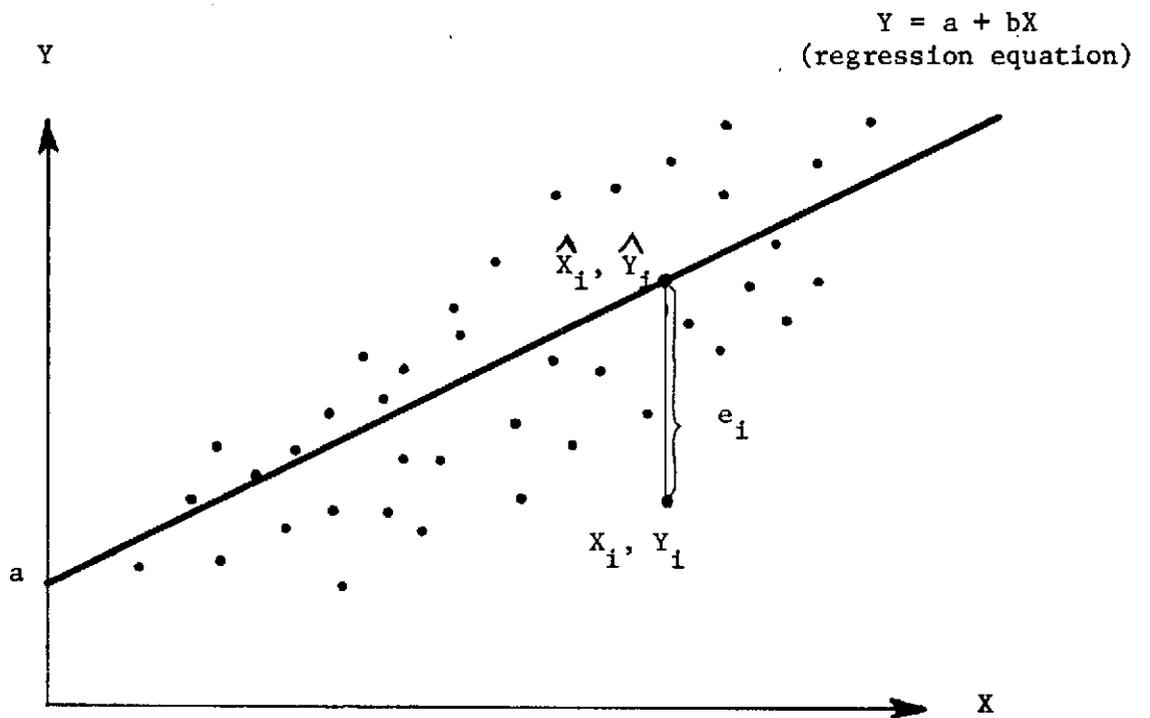
ei = difference between the plotted value Y_i and the calculated value Y_i or deviation

X_i, Y_i = actual values

$\widehat{X}_i$, $\widehat{Y}_i$ = estimated values

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Since $e_i = Y_i - \hat{Y}_i$ and we wish to sum all of the squares of i's,

$$S = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (Y_i - a - bX_i)^2. \qquad (A-1)$$

In order to minimize this expression we can take the first derivatives with respect to a and b and set these quantities equal to zero.[*]

$$\frac{\partial s}{\partial a} = (-2) \sum_{i=1}^{n} (Y_i - a - bX_i) \qquad (A-1a)$$

$$\frac{\partial s}{\partial b} = 2 (-X_i) \sum_{i=1}^{n} (Y_i - a - bX_i) \qquad (A-2a)$$

and from (1a)

$$\sum_{i=1}^{n} (Y_i - a - bX_i) = 0 \qquad (A-1b$$

from (1b)

$$\sum_{i=1}^{n} X_i (Y_i - a - bX_i) = 0 \qquad (A-2b)$$

Rearranging equations (1b) and (2b) we get

$$\sum_{i=1}^{n} Y_i - na - b \sum_{i=1}^{n} X_i = 0 \qquad (A-1c)$$

and

$$\sum_{i=1}^{n} X_i Y_i - a \sum_{i=1}^{n} X_i - b \sum_{i=1}^{n} X_i^2 = 0 \qquad (A-2c)$$

---

[*]Draper, N. R. and Smith, H., 1966, p. 10.

or: $\quad an + b \sum\limits_{i=1}^{n} X_i = \sum\limits_{i=1}^{n} Y_i$ $\hspace{4cm}$ (A-1d)

$$a \sum_{i=1}^{n} X_i + b \sum_{i=1}^{n} X_i^2 = \sum_{i=1}^{n} X_i Y_i \qquad\qquad \text{(A-2d)}$$

Generally equations (1d) and (2d) are referred to the first and second normal equations. Solving equation (2d) we find the constant a,

$$a = \frac{\sum\limits_{i=1}^{n} Y_i - b \sum\limits_{i=1}^{n} X_i}{n} . \qquad\qquad \text{(A-3)}$$

Substituting (3) into (2d) we obtain

$$\frac{\sum\limits_{i=1}^{n} Y_i - b \sum\limits_{i=1}^{n} X_i}{n} \left(\sum_{i=1}^{n} X_i \right) + b \sum_{i=1}^{n} X_i^2 = \sum_{i=1}^{n} X_i Y_i ,$$

$$\frac{\left(\sum\limits_{i=1}^{n} X_i\right)\left(\sum\limits_{i=1}^{n} Y_i\right)}{n} - b \frac{\left(\sum\limits_{i=1}^{n} X_i\right)\left(\sum\limits_{i=1}^{n} X_i\right)}{n} +$$

$$b \sum_{i=1}^{n} X_i^2 = \sum_{i=1}^{n} X_i Y_i ,$$

$$b \left[\sum_{i=1}^{n} X_i^2 - \frac{\left(\sum\limits_{i=1}^{n} X_i\right)^2}{n} \right] = \sum_{i=1}^{n} X_i Y_i - \frac{\left(\sum\limits_{i=1}^{n} X_i\right)\left(\sum\limits_{i=1}^{n} Y_i\right)}{n} , \text{ and}$$

$$b = \frac{\sum\limits_{i=1}^{n} X_i Y_i - \dfrac{\left(\sum\limits_{i=1}^{n} X_i\right)\left(\sum\limits_{i=1}^{n} Y_i\right)}{n}}{\sum\limits_{i=1}^{n} X_i^2 - \dfrac{\left(\sum\limits_{i=1}^{n} X_i\right)^2}{n}} \qquad\qquad \text{(A-4)}$$

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However,

$$\left(\sum_{i=1}^{n} X_i Y_i\right) - \frac{\left(\sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i\right)}{n} = \sum_{i=1}^{n} X_i Y_i - n \frac{\left(\sum_{i=1}^{n} X_i\right)}{n} \frac{\left(\sum_{i=1}^{n} Y_i\right)}{n} ,$$

$$= \sum_{i=1}^{n} X_i Y_i - n \bar{X} \bar{Y} ,$$

where $\bar{X}$ = average of the independent variable and $\bar{Y}$ = average of the dependent variable so,

$$\sum_{i=1}^{n} X_i Y_i - \frac{\left(\sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i\right)}{n} = \sum_{i=1}^{n} X_i Y_i - n \bar{X} \bar{Y} - n \bar{X} \bar{Y} + n \bar{X} \bar{Y} ,$$

$$= \sum_{i=1}^{n} X_i Y_i - \bar{X} \sum_{i=1}^{n} Y_i - \bar{Y} \sum_{i=1}^{n} X_i + n \bar{X} \bar{Y} ,$$

$$= \sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y}) . \qquad (A-5)$$

From the denominator of Equation A-4

$$\sum_{i=1}^{n} X_i^2 - \frac{\left(\sum_{i=1}^{n} X_i\right)^2}{n} = \sum_{i=1}^{n} X_i^2 - n \frac{\sum_{i=1}^{n} X_i}{n} \frac{\sum_{i=1}^{n} X_i}{n} ,$$

$$= \sum_{i=1}^{n} X_i^2 - n \bar{X}^2 ,$$

$$= \sum_{i=1}^{n} X_i^2 - n \bar{X}^2 - \sum_{i=1}^{n} X_i \bar{X} + \sum_{i=1}^{n} X_i \bar{X} ,$$

$$= \sum_{i=1}^{n} X_i^2 - \sum_{i=1}^{n} X_i \bar{X} - \sum_{i=1}^{n} X_i \bar{X} + n \bar{X} \bar{X} ,$$

$$= \sum_{i=1}^{n} X_i^2 - 2 \sum_{i=1}^{n} X_i \bar{X} + n \bar{X}^2$$

$$= \sum_{i=1}^{n} (X_i - \bar{X})^2 \text{, and} \qquad \text{(A-6)}$$

then from (4), (5) and (6) we have

$$b = \frac{\sum_{i=1}^{n} (X_i - \bar{X}) (Y_i - \bar{Y})}{\sum_{i=1}^{n} (X_i - \bar{X})^2} \qquad \text{(A-7)}$$

and if we choose to write the equation in another form,

$$a = \frac{\sum_{i=1}^{n} Y_i}{n} - b \frac{\sum_{i=1}^{n} X_i}{n}$$

$$a = \bar{Y} - b \bar{X} \qquad \text{(A-8)}$$

and the regression equation is

$$Y = a + b X_i$$

$$= \bar{Y} - b \bar{X} + b X_i \qquad \text{(A-9)}$$

$$Y = \bar{Y} + b (X_i - \bar{X}) . \qquad \text{(A-10)}$$

Statistical Indicators for Regression Equations

In selecting an equation there are several statistical indicators which have to be considered:

1. Coefficient of determination
2. Coefficient of correlation
3. Standard Error of estimate
4. Coefficient of variation
5. Standard error of the regression coefficient
6. F - test
7. β - coefficient

1. The coefficient of determination (R^2) provides an indication of the extent to which the observed data or Y values are in agreement with

the estimated regression or Y_i values.[*]

$$R^2 = \frac{\text{Regression sum of squares}}{\text{Total sum of squares}}$$

Given $Y_i = \bar{Y} + b (X_i - \bar{X})$

Rewriting $(Y_i - \bar{Y}) = b (X_i - \bar{X})$,

$$\sum (Y_i - \bar{Y})^2 = b^2 \sum (X_i - \bar{X})^2 \text{ , and the}$$

Regression SS $= b^2 \sum (X_i - \bar{X})^2$

Total SS $= \sum (Y_i - \bar{Y})^2$

$$R^2 = \frac{b^2 \sum (X_i - \bar{X})^2}{\sum (Y_i - \bar{Y})^2}$$

However it has been shown that

$$b = \frac{\sum (X_i - \bar{X}) (Y_i - \bar{Y})}{\sum (X_i - \bar{X})^2}$$

Therefore

$$R^2 = \left[\frac{\sum (X_i - \bar{X}) (Y_i - \bar{Y})}{\sum (X_i - \bar{X})^2} \right] \frac{\sum (X_i - \bar{X})^2}{\sum (Y_i - \bar{Y})^2}$$

$$= \frac{[\sum (X_i - \bar{X}) (Y_i - \bar{Y})]^2}{\sum (X_i - \bar{X})^2 \sum (Y_i - \bar{Y})^2}$$

Then the percentage of variation in the dependent variable that is explained by the regression model is given by:

$$R^2 = \frac{[\sum xy]^2}{\sum(x)^2 \sum(y)^2} \text{ , where } \begin{array}{l} x = (X_i - \bar{X}) \\ y = (Y_i - \bar{Y}) \end{array}$$

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[*]Williams, E. J., 1959.

2. The positive square root of the coefficient of determination, R, is known as the coefficient of correlation.

$$R = \sqrt{\frac{[\Sigma xy]^2}{\Sigma(x)^2 \; \Sigma(y)^2}}$$

3. The standard error of estimate is the measure of deviation of observed data about the regression line and is given by the following expression.

$$\delta_{y \cdot x} = \sqrt{\frac{\Sigma(Y_i - \hat{Y}_i)^2}{n - (p+1)}}$$

         p = No. of b_i associated with the independent variables

    (p+1) = total no. of parameters to be estimated

4. The coefficient of variation, CV, expresses the standard error of the dependent variable as a per cent of the mean.

$$CV = \frac{\delta_{x \cdot y}}{\bar{Y}} \;\; (100)$$

5. The standard error of the regression coefficient is simply the probable range (68% reliability) in which the "true" slope of the regression line can be expected to lie.[*]

$$\delta_{b_{x_i}} = \frac{\delta_{y \cdot x}}{\sqrt{\Sigma(X_i - \bar{x})^2}}$$

6. It is important to know whether or not the estimate coefficient,

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b_i, is significantly different from some hypothesized value of the regression coefficient, typically zero.[*]

$$F = \frac{\text{Mean Sq. Regression}}{\text{Mean Sq. Deviation}}$$

$$F = \frac{b_i^2 \ \Sigma (X_i - \overline{X})^2}{\int_{y \cdot x}^2}$$

Since this is an F-test with one degree of freedom in the numerator, $F = t^2$

which implies

$$t = \frac{b_i \quad \Sigma (X_i - \overline{X})^2}{\int_{yx}}$$

$$= \frac{\dfrac{b_i}{\int_{yx}}}{\sqrt{\Sigma (X_i - \overline{X})^2}}$$

$$\frac{b_i \ (-\beta)}{b_{xi}}$$

where $\beta = 0$ and we are testing to see if b_i is significantly different from zero.

If $n \geq 30$, then $t_{.05} = 1.96$

7. Usually the independent variables are expressed in different units (e.g., acres, cars, people, etc.). Unless the independent

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[*] Bureau of Public Roads, June, 1967. pp. 82-84.

variables are expressed in the same units of measurement, a
direct comparison of the coefficients in order to obtain their
relative importance in the equation is impossible. That is,
the relative magnitude of the coefficient will not indicate the
relative importance of a variable in the equation unless all
the variables are in the same units of measurement. However,
if each variable is expressed in terms of its standard deviation,
a direct measure of its relative importance in the equation is
made.[*]

$$\beta_i = \frac{b_i S_{x_i}}{S_y}$$

S_{x_i} = standard deviation of X_i

S_y = standard deviation of Y

b_i = the estimated regression of coefficient

Even after we develop a regression model that passes all
statistical tests of significance, we cannot overlook the reason-
ableness of our model. Other items to be considered are:[**]

1. <u>Choice of proper independent variable</u>. More often than
   not, more parameters will be available than are neces-
   sary. The problem then becomes one of selecting the
   proper variables from those available.

2. <u>Collinearity among variables</u>. Sometimes regression
   equations will fit the data well and still produce a
   questionable relationship. This could be caused by
   independent variables having a high degree of corre-
   lation among themselves. For such cases one of the
   variables has to be taken out of the regression equation.

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[*] Bureau of Public Roads. June, 1967. p. 85.

[**] <u>Ibid.</u>, p. 28.

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3. <u>Implications to forecasting</u>. The development of statistically reliable regression equations is for the ultimate purpose of forecasting trip volumes to some design year. It is recommended that equations be kept as simple and logical as possible.

4. <u>Analyzing observed against estimated dependent variable</u>. It is desirable to know if there are any particular cases in which the value of the dependent variable estimated by the regression equation differs considerably from the observed value. Such cases should be analyzed separately.

5. <u>The number of independent variables</u>. The regression equations should be developed with the minimum possible number of variables that still give good results. Past experience has shown that trip generation equations usually do not improve considerably after two or three independent variables have been added.

6. <u>Adequacy of range of survey data</u>. Relationships that are developed utilizing regression analysis are applicable only within the range of the data used to develop the equations. Additionally, the evaluation measures used are only applicable to the data used in the analysis.

7. <u>Regression coefficient</u>. Often the constant turns out to be quite large (negative or positive) in the final regression equation, and the initial reaction is usually an attempt to modify the equation in some way. The magnitude and size of the constant are of considerable consequence in the base year calibration and the design year forecast. Problems occurring in forecasting a high estimate of trip ends for a particular zone may result solely from the magnitude of the regression constant or low estimate, from a negative constant.

8. <u>Alternate relationships</u>. During the initial trip generation analysis it is wise to develop alternative relationships. The final choice of the equation to use could then be made on the basis of the statistical evaluation, the reasonableness of the relationships, the trip-land use relationships over time, and the indicated growth in trips. Also consideration may be given to the availability and reliability of the socio-economic data.

APPENDIX B

TRIP DISTRIBUTION MODELS

Fratar

The Frater method (Fratar, 1954) represents a logical extension of the simple growth factor method. In this technique, different growth factors are assigned to different zones. Future interzonal travel forecasts are derived from the present level of interzonal trips and the assigned zonal growth factors. The zonal growth factor, G_i, is simple the ratio of future to present trip generating activities:[*]

$$G_i = \bar{T}_i / T_i$$

where

T_i = present level of trip generation at zone i, and

$\bar{T}_i$ = future estimated level of trip generation at zone i.

When a growth factor technique such as Fratar's is used, it is necessary to make special adjustments to account for zones that are vacant at the present time but which have a potential for development in the future. A similar problem arises when changes of land use are foreseen.

The main inputs to the Frater model are the O-D tables and a table of growth factors. For each zone in the transportation study

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[*]Meyer, J. R. and M. R. Straszheim. Vol. I, 1971, p. 118.

origin and destination growth factors are assigned. These two factors do not have to be the same for any specific zone. The procedure of distributing trips by Fratar is an iterative process by which all origin trips/zone are factored first. This will alter the actual total trip destinations/zone, which may not agree with those desired. New destination factors for each zone are found which are equal to the desired trip destinations divided by the actual trip destinations. These new ratios are used for factoring all trip destinations/zone. This time the actual trip origins may not match the desired trip origins, and another iteration has to be done. The process is continued until a reasonable match between desired and actual trips (origin and destination) is obtained.

For computational purposes we may represent the technique as:[*]

$$F_{ij}(k+1) = T_{ijk} F_{jk} F_{ik},$$

$$F_{jk} = \frac{T_j}{\sum\limits_{i=1}^{n} T_{ijk}},$$

$$F_{ik} = \frac{T_i}{\sum\limits_{j=1}^{n} T_{ijk} F_{jk}}.$$

where

T_{ijk} = trips between i and j for iteration k,

F_{jk} = destination (column) factor j,

F_{ik} = origin (row) factor i,

T_j = final desired total for destination j,

T_i = final desired total for origin i,

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i = origin zone number, i = 1, 2, 3, . . . , n,

j = destination zone number, j = 1, 2, 3, . . . , n,

n = number of zone, and

k = iteration number, k = 1, 2, 3, . . . , m.

Note that one must calculate $\sum_{j=1}^{n} T_{ijk} F_{jk}$ before F_{ik} can be

calculated. Thus the mathematical formulation of this model represents a two-step process. The application of this process to all origin zones represents one iteration.

Intervening Opportunities Model

Samuel O. Stouffer introduced the concept of intervening opportunities in 1940 as a method of exploring the observed movement of people in a defined area. The model explores the theory that the number of people traveling a particular distance from a specific location is not dependent directly upon distance, but rather upon the spatial distribution of opportunities. Morton Scheineder, a member of CATS staff, applied the Intervening Opportunities Model to distribute, over all possible destinations, the actual destinations of all trips having a stated origin. The distinguishing feature of the model is its unique independent variable, intervening opportunities.

The intervening opportunity model assumes that the trip interchange between an origin and a destination is equal to the total trips emanating from the origin multiplied by the probability that each trip origin will find an acceptable terminal at the destination.

$$T_{ij} = O_i P (D_j) \tag{B-1}$$

where

T_{ij} = the trips between origin zone i and destination zone j,

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D_j = the total trips destinations attracted to zone j,

O_i = the total trip productions at zone i,

$P(D_j)$ = the probability that each trip origin at i will find destination j an acceptable terminal.

The model assumes two characteristics to determine $P(D_j)$:

1. The size of the destination zone, and

2. The order in which the destination zone is encountered as trips proceed away from the origin.

$P(D_j)$ may also be expressed as the difference between the probability that the trip origins at i will find a suitable terminal in one of the destinations, ordered by closeness to i up to and including j, and the probability that they will find a suitable terminal in all destinations up to but excluding j.

$$T_{ij} = O_i \; [P\;(A) - P\;(B)] \qquad (B-2)$$

where

A = sum of all destinations for zones, in terms of closeness, between i and j and including j,

B = sum of all destinations for zones between i and j but excluding j,

$A = B + A_j$, and

$$P(D_j) = [P\;(A) - P\;(B)] \qquad (B-3)$$

The probability that a trip will terminate within some volume of destination points is equal to the product of the following two probabilities:

- that this volume contains an acceptable destination
- that an acceptable destination closer to the origin zone has not been found

Expressed as a differential

$$dP = (1 - P)\; L\; d\; V \qquad (B-4)$$

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where

> $P = P(V) =$ Probability that trip has terminated within the destination voluem V, lying earlier in order of consideration.
>
> L $=$ Probability density (probability per destination) of destination acceptability at the point of consideration.
>
> V $=$ Volume of destination points (destination trip ends) within which the probability of a successful terminal is to be calculated.

Dividing both sides of (4) by $(1 - P)$ we have

$$\frac{dP}{(1 - P)} = L \, d \, V \tag{B-5a}$$

$$-\ln (1 - P) = LV + \ln C \tag{B-5b}$$

$$\ln (1 - P) + \ln C = -LV \tag{B-5c}$$

$$\ln (C) (1 - P) = -LV \tag{B-5d}$$

$$C (1 - P) = e^{-LV} \tag{B-5e}$$

$$1 - P = (1/c) \, e^{-LV} \tag{B-5f}$$

for $P = 0$ and $V = 0$

$$1 = (1/c) \, e^{-0} \text{ and}$$

$$c = 1 \tag{B-6}$$

From (5b) and (6) we get

$$-\ln (1 - P) = LV$$

$$\ln (1 - P) = -LV$$

$$(1 - P) = e^{-LV}$$

$$P(V) = 1 - e^{LV} \qquad (B-7)$$

and

$$P(A) = 1 - e^{-LA} \quad \text{and} \quad P(B) = 1 - e^{-LB} \qquad (B-8a,b)$$

Substituting (8a, b) into (2) we have

$$T_{ij} = 0_i [1 - e^{-LA} - (1 - e^{-LB})] \qquad (B-9)$$

$$= 0_i [e^{-LB} - e^{-LA}]$$

$$= 0_i [e^{-LB} - e^{-L(B+A_j)}] \quad \text{and}$$

with the more common notation being

$$T_{ij} = 0_i [e^{-LD} - e^{-L(D+D_j)}] \qquad (B-10)$$

Spatial distribution in the Intervening Opportunities Model is then measured in terms of intervening opportunities determined by arraying the available destinations in all zones by travel time from the zone of origin. This model is calibrated by varying the probability values (L) until the simulated trip distribution produces the observed trip distribution. This is tougher than in the Gravity Model calibration because L determines both the percentage of the total trips to be distributed and their distribution to destination zones.

Four parameters must be known before T_{ij} can be computed:[*]

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[*] Jarema, F., Pyers and Reed, 1967.

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1. The number of trips originating in a zone (O_i).

2. The number of trips ending in a zone D_j.

3. Travel time is a measure of the zonal spatial separation. It is used as a means of ranking all zones in decending order from any given zone.

4. The L value, or probability factor, is empirically derived and describes the rate of trip decay with increasing trip destinations and trip lengths.

An iterative technique similar to that used in the Gravity Model is used to bring the calculated destination totals in agreement with the desired actual destination totals. The iterative process can be expressed by the following mathematical expression.[**]

$$D_{jk} = \frac{D_j}{\sum\limits_{i=1}^{n} T_{ij}} \; D_{j(k-1)}$$

where

D_{jk} = adjusted total trip destinations, zone j (iteration k),

D_j = desired total trip destinations, zone j,

$D_{j(k-1)}$ = previously used total trip destinations, zone j, (iteration k-1), and

$\sum\limits_{i=1}^{n} T_{ij}$ = actual total trip destinations for zone j.

The Competing Opportunities Model

The competing opportunity model has as its basic concept that opportunities or destinations compete for trips within equal travel time, travel distance or travel cost bands as measured from the zone of origin. Within a given band, every opportunity has an equal probability of acceptance. The probability that trips will

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[**]Bureau of Public Roads, June, 1970.

distribute to a certain zone is the product of two independent probabilities, the probability of attraction and the probability of satisfaction. The mathematical formulation of the model is as follows:[*]

$$T_{ij} = 0_i \, \rho_{aj} \, \rho_{sj}$$

where

T_{ij} = trip interchange

0_i = trip origins in zone i

ρ_{aj} = probability of attraction- and

ρ_{sj} = probability of satisfaction

and

$$\rho_{aj} = \frac{\text{destinations available in zone } j}{\Sigma \text{ destinations available up to and including band } m}$$
(band m contains band j)

$$= \frac{D_j}{\sum\limits_{k=1}^{m} D_k} \, , \tag{B-11a}$$

$$\rho_{sj} = 1 - \frac{\Sigma \text{ destinations up to and including band } m}{\Sigma \text{ total destinations in study area}} \, ,$$

$$\rho_{sj} = 1 - \frac{\sum\limits_{k=1}^{m} D_k}{\sum\limits_{k=1}^{n} D_k} \tag{B-11b}$$

where

k = any time band

m = time band into which j falls

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[*]Heanve, K. and C. Pyers. 1966.

D_k = destinations available in time band k

n = last time band as measured from zone i, and

D_j = destinations available in zone j.

The competing opportunities model is calibrated by varying the width of attracting bands until the trip length characteristic of the synthetic trips correspond to the trip length characteristic of the surveyed trips. This model has been found to be very difficult to calibrate because no systematic calibration procedure is available.

Linear Programming

This is a more deterministic method that is not very applicable to urban transportation mainly because of the many undefined variables encountered. The model nevertheless is very simple and effective for more controllable distribution systems such as bus routings, distribution systems between production centers and warehouse centers under a common management, etc.

The model can be formulated as follows: Assume that there are m production nodes, where each node produces a_i ($i = 1, 2, 3, \ldots, m$) entities (goods, trips, etc.). Also assume there are n attraction nodes where each node has a demand of b_j ($j = 1, 2, 3, \ldots, n$) entities. The cost of transporting one entity from production node i to attraction node j is C_{ij}. The objective of this method is to establish a distribution that exhausts all production nodes supplies and fulfills all attractions nodes demand at a minimum cost. The maximum number of entities that can be shipped from production node i to attraction node j is X_{ij} ($i = 1, 2, 3, \ldots m; j = 1, 2, 3, \ldots, n$). Figure B-1 shows schematically the physical model.

The method can be stated mathematically as follows:

$$\text{Min. } z = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} X_{ij} \qquad \text{(B-12)}$$

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Production   Attraction

a_1 b_1

a_2 b_2

a_3 b_3

a_i X_{ij} b_j

b_n

a_m
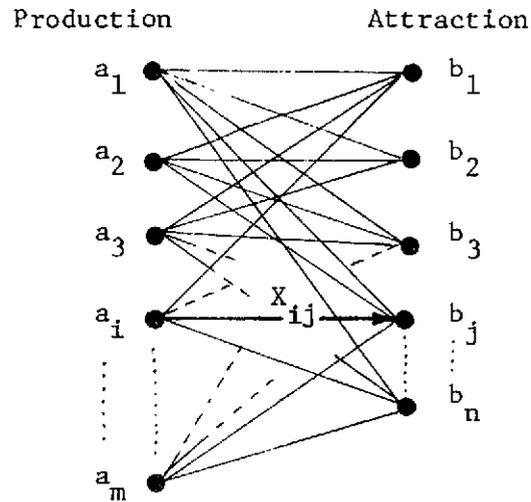
FIGURE B-1.   LINEAR MODEL (TRANSPORTATION)
DESCRIPTION

subject to the following constraints

$$X_{ij} \geq 0 \quad \text{for all i and j} \tag{B-12a}$$

and

$$\sum_{j=1}^{n} X_{ij} = a_i \quad i = 1, 2, 3, \ldots, m \tag{B-12b}$$

$$\sum_{i=1}^{m} X_{ij} = b_j \quad j = 1, 2, 2, \ldots, n \tag{B-12c}$$

Because of the existence of the balanced condition (supply = demand)
we have from Equation B-12b that

$$\sum_{j=1}^{n} \sum_{i=1}^{m} X_{ij} = \sum_{i=1}^{m} a_i , \tag{B-13a}$$

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from Equation B-12c that

$$\sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} = \sum_{j=1}^{n} b_j \qquad (B-13b)$$

and

$$\sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j \qquad (B-13c)$$

where

C_{ij} = cost of transporting one entity from node i to node j

X_{ij} = amount of entities transported from node i to to node j

a_i = number of entities produced at node i

b_j = number of entities attracted at node j

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